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FLATHEAD BASIN FOREST PRACTICES  
WATER QUALITY AND FISHERIES  
COOPERATIVE PROGRAM

EVALUATION OF HISTORICAL  
SEDIMENT DEPOSITION  
RELATED TO LAND USE  
THROUGH ANALYSIS OF LAKE SEDIMENTS

BY CRAIG N. SPENCER



JUNE 1991

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## ABOUT THIS REPORT

This report is one of ten individual studies conducted for the Flathead Basin Forest Practices/ Water Quality and Fisheries Cooperative Program. The Cooperative Program was administered by a Coordinating Team representing the Montana Department of State Lands Forestry Division, the Flathead National Forest, Plum Creek Timber Company, L.P., the Montana Department of Fish, Wildlife and Parks, the Montana Department of Health and Environmental Sciences' Water Quality Bureau, the University of Montana, and the Flathead Basin Commission.

The Cooperative Program's specific objectives were (1) to document, evaluate, and monitor whether forest practices affect water quality and fisheries within the Flathead Basin, and (2) if detrimental impacts exist, to establish a process to utilize this information to develop criteria and administrative procedures for protecting water quality and fisheries.

The ten individual studies included the evaluation of: (1) specific practices at the site level, (2) accumulation of practices at the watershed level, (3) general stream conditions, (4) water quality variables relative to levels of management activity in small watersheds, (5) fish habitat and abundance relative to stream variables influenced by forest practices at the watershed level, (6) long-term changes in large-stream dynamics related to historical records of natural and man-related disturbances, and (7) changes in lake sediments relative to historical records of natural and man-related disturbances. A *Final Report* was developed which contains summaries of each of the studies, a set of summary conclusions and recommendations, and a formal response to the recommendations by the land management organizations which administered the Cooperative Program.

## CONTRIBUTORS

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Montana Department of Fish, Wildlife and Parks  
Flathead Basin Commission  
Montana Environmental Quality Council  
Montana Chapter of the American Fisheries Society  
Governor's Office, State of Montana

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WATER QUALITY AND FISHERIES  
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SEDIMENT DEPOSITION  
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JUNE 1991

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EVALUATION OF HISTORICAL SEDIMENT DEPOSITION  
RELATED TO LAND USE  
THROUGH ANALYSIS OF LAKE SEDIMENTS

Final Report

Prepared by

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June 1991

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## INTRODUCTION

One of the biggest environmental concerns with regard to timber harvest is the potential for enhanced erosion and transport of sediment to surface waters. Increased sediment loadings are considered undesirable as they may degrade gravel spawning habitat used by stream fish (see Weaver and Fraley report, this volume). Furthermore, since sediments represent a major source of water-borne nutrients (Mortimer 1941; Perry and Stanford 1982) increased erosion and sediment transport may accelerate the eutrophication process in surface waters, especially in lakes and reservoirs.

Current debate over the impact of logging activities on water quality in the Flathead Basin, located in northwest Montana, is hampered by a scarcity of quantitative data on conditions prior to the commencement of timber harvest. Early logging activities began 50 or more years ago in many parts of the Basin. However, most water quality monitoring efforts were initiated only within the last 10 to 20 years or less. Without pre-logging data, it is difficult to assess the impact of harvest activities on water quality in the Flathead Basin.

Previous studies in other areas have documented increased sediment loadings to surface waters resulting from timber harvest activities (Likens et al. 1970, Lowe et al. 1986). Nevertheless, it may not be appropriate to extrapolate findings from other areas to the Flathead Basin. A number of streams in the Flathead Basin are flanked by steep, naturally occurring, unstable stream banks composed of sand, silt and clay. The presence of these erosive deposits may result in naturally elevated sedimentation rates in the Basin. Thus it is possible that erosion of sediments associated with logging activities in the Flathead Basin may be minor in comparison to natural sediment loadings.

The vast majority of suspended stream sediments carried into large deep lakes are deposited within the quiescent lake environment. Significant changes in surface erosion and sediment transport within the catchment of a lake should be reflected in changes in the sediment character and the rate of sediment accumulation in the lake (Berglund 1986). Thus, undisturbed sediments deposited on the bottom of lakes contain a record of the past history of sedimentation from their respective catchments. Modern paleolimnological techniques are available which allow estimation of past sedimentation rates through detailed analysis of the "paleo" record preserved in the lake sediments (Berglund 1986). A record of past changes is most evident in sediments deposited in the deep-water (profundal) region of the lake. This environment is much more stable than nearshore, shallow lake, or stream environments; deep lake sediments may remain largely undisturbed for thousands of years.

One of the more notable paleolimnological studies, by Hutchinson et al. (1970), documented increased sedimentation rates in a lake in Italy (Lago di Monterosi) over 2000 years ago, coinciding with construction of the Roman Road, the Via Cassia, in about 171 B.C. Numerous studies report changes in sedimentation rates in other lakes which correlate with various land disturbance activities including timber harvest, plowing of fields, and road building (Davis 1975, Batterbee et al. 1985, see reviews in Berglund, 1986). Although there have been previous paleolimnological studies in the Flathead Basin (Moore et al. 1982), none have quantified recent sedimentation rates.

The present research was initiated to study the historical record of sediment deposition over the last 100-150 years in three lakes in the Flathead Basin (Figure 1). Whitefish Lake and Swan Lake are located in catchments that have a history of land disturbance activity (primarily timber harvest and road building) throughout much of this century. Lake McDonald is located in Glacier



National Park, and its catchment has not been logged. However, a road was constructed from the bottom to the top of the catchment during the 1920s and 30s.

## METHODS

The sediments in the deep lakes sampled in this study are soft and unconsolidated, particularly in the surface layers where 90% or more of the sediment volume is composed of water. These soft sediments are easily distorted by most coring devices. Before developing the freeze coring technique described below, I experimented with a number of other coring devices. Previous researchers report successful collection of undisturbed lake sediments with gravity corers, piston corers, and box corers. However, lengthy efforts with these more conventional devices produced sediment cores which were obviously distorted during the collection process. I even developed a piston corer which could be slowly driven into the sediments by SCUBA divers. The near surface layers of these cores still appeared distorted by the collection process.

Sediment cores for this study were collected using a freeze coring technique modified from Shapiro (1958). The technique involved filling a weighted aluminum cylinder (4" diam.) with a mixture of dry ice and butanol. The bubbling mixture was then capped with a large rubber stopper fitted with a long vent hose (5mm diam.). The sublimating dry ice created positive pressure within the capped cylinder which, together with the long vent hose, prevented water from entering the cylinder during submergence in the lake.

The torpedo-shaped cylinder was attached to a line and lowered over the side of a boat. The cylinder travelled quickly through the lake water, penetrating into the sediments at the bottom of the lake. The cylinder was left in the sediments for 10 minutes during which time the surrounding sediments froze to the outside of the cylinder. The cylinder was retrieved from the sediments using a winch located on the boat. Upon retrieval, an outer layer of unconsolidated sediments was rinsed from the outer margin of the frozen core, revealing a 1-2cm thick layer of frozen sediments surrounding the aluminum cylinder. The cap on the top of the cylinder was removed and the remaining dry ice mixture was poured out and replaced with hot water. Within 5-10 seconds, the frozen sediments readily slid off the cylinder. Frozen cores were photographed, placed

in a polyethylene bag, and temporarily stored in a cooler with dry ice. Upon return to the laboratory, the cores were stored in a freezer.

A number of freeze-cores were collected from each of the study lakes. A single core from each lake was selected for detailed analysis. Criteria for core selection included minimal evidence of sediment disturbance and appropriate length (25-30cm). The cores selected for detailed analyses were all collected from the deep region of each lake, well away from major tributaries (Figures 2-4).

The frozen cores were sectioned using an electric band saw. A slice running the length of the core was first sawed from the core, and archived in a freezer. The remainder of the core was sliced in horizontal sections approximately 1 cm thick. Prior to sectioning, a wooden ruler was frozen inside each core, with the top of the ruler placed at the sediment-water interface. In this way, a small section of the ruler remained attached to each slice, allowing determination of the exact depth of each section.

Prior to analysis, the frozen core sections were placed in plastic (Whirlpak) bags, and thawed. The contents of each bag were thoroughly mixed by repeated withdrawal and extrusion through a plastic syringe. Known volumes (10-12mL) were then collected from each bag with a graduated syringe. Samples were weighed for determination of wet density, and then freeze dried for subsequent determination of dry density. Dates were established along the length of the core using a naturally occurring radioisotope ( $^{210}\text{Pb}$ ) which decays at a known rate (half life=23 years). By measuring the activity of  $^{210}\text{Pb}$  in each section, it was possible to establish a time line of sediment deposition dates along the length of each core (Appleby and Oldfield 1983).

Radioisotope activity was measured via low background gamma counting (Appleby et al 1986). Samples were counted with a well-type intrinsic germanium detector (EG&G Ortec) and a 4096-channel pulse height analyzer. Sediment samples were pressed into plastic test tubes to a nominal depth of 30 mm and then weighed. A layer of epoxy was then placed over the samples to seal them. Direct estimates of background (supported)  $^{210}\text{Pb}$  activity were estimated using  $^{214}\text{Bi}$ . Ages were calculated from the excess (unsupported)  $^{210}\text{Pb}$  activity using the constant rate of supply (CRS) model (Appleby and Oldfield 1983).

In undisturbed sediments, this technique has been shown to be useful in dating sediments deposited up to 150 years ago. Older  $^{210}\text{Pb}$  dates, particularly those over 100 years ago are probably less precise due to low  $^{210}\text{Pb}$  activity resulting from radioactive decay of this isotope which loses half its activity every 23 years.

An independent technique was used for an alternate estimate of the location of sediments deposited in 1963. Atmospheric testing of atomic weapons peaked in 1963, and previous studies have documented a peak in  $^{137}\text{Cs}$  activity in lake sediments deposited in 1963, due to global fallout of the radioactive decay particles (Pennington et al. 1973). Comparison of dates from the three cores indicated close agreement between the two dating methods.

Once chronological ages were determined for each section of the core, sediment accumulation rates ( $\text{mg dry wt}/\text{cm}^2/\text{yr}$ ) were estimated for the period spanned by each  $\sim 1\text{cm}$  thick core section. These rates were calculated by multiplying the width of the core section ( $\text{cm}$ ) by the dry weight density of the section ( $\text{mg}/\text{cm}^3$ ) and dividing by the length of time (years) spanned by the section. These rates represent mean sedimentation values which occurred over the time span of each  $1\text{cm}$  thick section of sediment. The calculated time intervals spanning each section of sediment varied as a function of the overall sedimentation rate occurring during the period. For example, during periods of relatively low sedimentation in Whitefish Lake in the 1800s it took 10-20 years to accumulate  $1\text{ cm}$  of sediment on the lake bottom (Figure 8). Thus mean sedimentation rates estimated for this time period span 10-20 years. Consequently the horizontal bars shown in Figure 8 are wide in the late 1800s. During periods of relatively high sedimentation, just after 1900 and again in the early 1930s,  $1\text{ cm}$  of sediment accumulated in only a few years in Whitefish Lake. Thus, mean sedimentation rates estimated during these periods span shorter time intervals than during periods of low sedimentation. As a result, the width of the sediment rate bars in Figure 8 are narrower during periods of elevated lake sedimentation

One core from each lake was chosen for dating. Ideally, several cores would have been analyzed from each lake; however, the available budget was not sufficient for multiple core analysis. Although only one core was analyzed in detail from each lake, the selected cores appeared to be representative of whole-lake conditions in Whitefish and Lake McDonald. For example, distinct patterns of horizontal banding noted in the dated cores also were clearly visible



in the same relative location in other cores collected from the same lake. Since no banding was observed in cores collected from Swan Lake, visual cross-comparisons between cores was not possible.

It is important to note that the present analyses were not designed for quantitative establishment of whole-lake sediment budgets over the last 125 years. Thus the study results should not be used to estimate total sediment loadings to the study lakes over the period of record. Such analyses would require analyses of a number of cores collected from various parts of each lake. Rather, the present analysis simply utilized the stable deep-lake sediments as a continuous monitor of relative changes in the rate of deposition of fine sediment transported to the lake environment. Thus, the absolute sedimentation rates ( $\text{mg}/\text{cm}^2/\text{yr}$ ) estimated for Whitefish, McDonald, and Swan Lakes are of less interest than the relative change in these rates over time.

Previous studies have identified construction of logging roads as the largest source of increased sediment loading associated with logging activities. Correlations between lake sedimentation rates and timber harvest and associated road building activities were evaluated using timber harvest acreages and sediment coefficients. Foresters in the Flathead Basin have developed coefficients for relative changes in delivery of sediment to surface waters resulting from new roads (Mike Enk personnel communication, FNF Plan). These sedimentation coefficients decline over time as the roads stabilize. During the first year following construction, the sediment contribution from the road is listed as 100%. During second year the relative sediment contribution from the road declines to 60%, then 30% for two years, and finally 15% in the fifth year. Unfortunately, I do not have a chronological history of new road construction in the study catchments. However, data from the Flathead National Forest shows a direct relationship ( $p < 0.001$ ) between timber harvest acreage and road construction in other areas of the Flathead Basin. Based on this relationship together with the road sedimentation coefficients described above, I developed a relative index of past logging road history in each catchment as follows. The sediment coefficients were multiplied by timber harvest acreages and summed over a five year period to derive a running five year cumulative index to timber harvest and related road activity. Because the timber harvest data are expressed as acres/year, the cumulative index carries these same units. Changes in this index should provide a relative measure of sediment

loadings expected from logging roads for a period of 5 years following construction.

## RESULTS AND DISCUSSION

### General description of the cores

Photographs of the three cores chosen for study are shown in Figures 5-7. Each photograph is accompanied by a graph containing a density profile of the core. The density profiles and photographs are oriented in such a way that the vertical scales are identical. Distinct horizontal bands which correlate with changes in sediment density are readily apparent in the cores from Whitefish and McDonald.

These bands suggest that the type and/or composition of sediments deposited in the lake changed periodically over time. Changes in sediment composition also are evident from measurement of the sediment density throughout the length of these two cores (Figures 5,6). A constant supply of sediments should result in a sediment density profile that increases gradually with depth as a result of compaction by overlying sediments. While there is a trend of increasing density with depth in the cores, this trend is not monotonic. Rather it is characterized by a series of rather abrupt changes in the Whitefish and McDonald cores. Some of these changes coincide with changes in the banding pattern visible in these cores. For example the sediment density in the Whitefish Lake core increased significantly in the vicinity of the distinct light grey band ~13.5 cm below the surface (Figure 5). The dark black band at 15 cm appears correlated with a decline in density. Similarly in Lake McDonald, the distinct visual bands at 18.5 and 24 cm correspond with distinct increases in sediment density (Figure 6). (Note: unfortunately, some visual characteristics noted in the original photographs were obscured by the photocopy process used to produce Figures 5-7).

The lack of visual banding in the Swan Lake core together with the relatively uniform density profile (Figure 7) suggests that abrupt changes in the composition of sediment deposited in the lake may not have occurred over the period of record. Thus density, but not necessarily sedimentation rate, is fairly uniform throughout the core. Or, the near surface sediments in Swan Lake may



have undergone "bioturbation" by invertebrates living in the surface layers of the sediments. Mixing of the near surface layers by burrowing organisms has been noted in other paleolimnological studies (Robbins et al. 1977). This activity may cause a blending of the sediments, thereby masking abrupt visual changes or density changes in the core. In some cases, such mixing may render the cores useless for interpretation of recent sedimentation history. Such was not the case for Swan Lake, since dates from the core declined with depth, from the top to the bottom of the core.

### Whitefish Lake

The Whitefish Lake catchment has been subject to a number of land disturbance activities (both man-induced and natural) which may have influenced the sedimentation rate in this lake. These various activities will be chronologically compared with the lake sedimentation rates for evaluation of potential causal relationships.

#### Natural disturbances

There were four years in which fires burned 500 acres or more in the catchment during the period of record. The greatest acreage burned in 1910, when 5562 acres burned, representing 6.7% of the total catchment area (Table 1).

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TABLE 1. Acreages burned by fires in the Whitefish Lake catchment. The table includes only those years when fires cumulatively burned more than 500 acres.

---

YEAR	Area burned (acres)	% of catchment burned
1910	5562	6.7
1919	2458	3.0
1926	3036	3.7
1937	750	0.9

---

Data collected in this study do not show evidence of large changes in sedimentation following any of these fires (Figure 8). The sedimentation rate did increase during the time interval of the 1910 fire and some of this increase may have been attributed to fire. However, human land disturbance activities (described later) also occurred in the basin at this time; thus specific fire effects are difficult to discern. Moreover no obvious ash layer was visible in the lake core around 1910. The mean sedimentation rates shown in Figure 8 were in the midst of decade-long periods of decline during the time period of two other fires (1919, 1937). Sedimentation rates increased slightly during the interval spanning the 1926 fires; however, extensive human disturbance of the catchment commencing in the late 1920's complicates determination of actual cause and effect. Nevertheless, a thin layer of black ash is clearly visible in the sediment core at a depth corresponding to the time period around 1926 (Figure 5). This distinct ash layer undoubtedly resulted from transport of ash from the 1926 fires into the lake (either from the air or via streams). One of the 1926 fires, called the Hellroaring Fire, burned down to the shore of Whitefish Lake, and extended into the area now encompassed by the Big Mountain Ski Resort in the Whitefish Mountains.

Discussions with foresters (T. Vars, D. Klehm) and soil scientists (D. Sirucek) familiar with soils in the catchment indicate that, with the exception of the 1926 fire, there was little visible evidence of surface erosion in the basin following past fire activity. However, following the 1926 fire, there was considerable surface erosion, and some of resulting gullies are still visible, particularly in the Fitzsimmons Creek drainage, which lies just outside the Whitefish Lake drainage near the headwaters of Swift Creek. Ash carried by stream waters together with airborne transport of ash to the lake surface during the fire likely explain the ash layer visible in the core. Nonetheless, changes in the sediment record resulting from the 1926 fire appear short-lived, and of small magnitude, compared to human disturbance events described later.

Flooding is another natural disturbance activity which may influence lake sedimentation rates. It is well known that over the course of a given year, the majority of sediment transport by Rocky Mountain streams occurs during spring run-off. Thus during unusually large spring flood events, one might expect to observe increased sedimentation rates in the study lakes. Three major spring

floods have been recorded in the Flathead Basin during the period of record. These occurred in 1894, 1964 and 1974. The largest of the three occurred in 1894, when severe spring floods produced the highest flood waters ever observed in the Flathead Basin. Whitefish Lake was raised to its highest recorded level, 9.5 feet above the low water mark (Schafer and Engelter, 1973). The sedimentation rate estimated for the core section spanning 1894, was 26 mg/cm<sup>2</sup>/yr compared to 20 mg/cm<sup>2</sup>/yr during the previous period. For a flood of such magnitude, this increase in sedimentation rate was relatively small in comparison to subsequent changes. Furthermore, the 1894 flood was not the only land disturbance event in the catchment. Early land clearing and timber harvest activities commenced in the catchment in the late 1880's and early 1890's. The first sawmill on the Whitefish River, just below the lake, was built in 1891. Nevertheless, in 1894, the vast majority of land in the Whitefish Lake catchment remained undisturbed by human activities. Thus it appears that major floods in undisturbed catchments have a relatively small impact on deposition of fine sediments in lakes in comparison to extensive human disturbance activities (discussed later).

More detailed analysis of the lake sediment record over shorter time increments (<1 year) would likely reveal increased sediment deposition for a short time following major flood events such as 1894. However, such increases were not sufficient to elevate the mean sedimentation rates over the longer intervals measured in this study. Shorter water retention time in lakes during flood events may lessen their impact on lake sedimentation rates. Nevertheless, the majority of sediments entering Whitefish Lake are deposited in the lake, even during spring run-off events (Golnar 1985).

The 1964 flood was the next most intense flood event recorded in the valley. The sedimentation rate in Whitefish Lake reached levels up to 88 mg/cm<sup>2</sup>/yr during this time period; however, there were significant timber harvest activities (described later) occurring in the basin over the same time interval. Thus it is difficult to isolate the effects of the flood. The smallest of the three floods occurred in 1974. As with the 1964 flood, it is difficult to determine the effect of this flood on lake sedimentation rates. The sedimentation rate was well above background levels during this period; however, significant timber harvest activities occurred during this time period as well.

The 1964 and 1974 floods washed out numerous culverts and several bridges in the Swift Creek drainage. Observations by local foresters (T. Vars, D.



Klehm) indicate that widespread surface erosion did not appear to have taken place in the Whitefish Lake catchment during these floods. Nevertheless, the floodwaters were reported very muddy and carried high levels of suspended sediment. These foresters speculated that increased sediment loads associated with these floods likely came from transport of sediment previously deposited in the stream channels, together with erosion of unconsolidated banks which are prominent along Swift Creek. More detailed discussion of these floods will follow in subsequent coverage of human disturbance activities.

Another natural disturbance event which may have influenced the sedimentation rate in Whitefish Lake was the 1980 eruption of Mt. St. Helens. This eruption produced a fallout of volcanic ash across western Montana. There is no visible ash layer in the study cores, and lake sedimentation rates did not appear to increase during this time period. Nevertheless, it is possible that the most recent sedimentation rates would have been lower in the absence of volcanic ash deposition.

### Human disturbances

1865-1929. Distinct correlations between natural disturbance events and changes in fine sediment deposition in Whitefish Lake are difficult to make. By contrast, correlations between human activities in the basin and lake sedimentation are more readily apparent. Prior to the arrival of the earliest Europeans settlers in the late 1880's, the Whitefish Lake catchment was heavily forested and virtually undisturbed by human activity. Human activities in the catchment apparently were limited to an occasional small Indian fishing encampment near the outlet of Whitefish Lake (Trippett 1956, Schafer and Engelter 1973). Mean sedimentation rates in Whitefish Lake during this pre-settlement period were the lowest recorded over the 125 year period of record. Between 1865 and 1886, the estimated mean sedimentation rate was approximately 20 mg/cm<sup>2</sup>/yr (Figure 8).

Due to the low sedimentation rate during the pre-settlement period, the mean sedimentation rate shown in Figure 8 spans a relatively long time interval (21 years). Annual sedimentation rates likely varied within this long interval. However, I have no evidence to suspect that large changes occurred during the period from 1865-1886. In the first place, the mean sedimentation rate from 1865-1886 was comparable to the subsequent rate from estimated between

1886 and 1900. Second, if some unknown, natural disturbance event occurred and resulted in large short-term changes in the seemingly stable, pre-settlement sedimentation rate then one would expect to see changes reflected in the visual character of the sediment core. No distinct visual changes were evident in the core over the 30 year pre-settlement period.

The sedimentation rate increased slightly during the period from 1886 - 1900, concurrent with the 1894 flood and early logging activity around Whitefish Lake. The earliest European settlers were primarily trappers and lumbermen (Schafer and Engelter 1973). A sawmill was constructed at the outlet of Whitefish Lake in 1891. Small logging operations were concentrated at the southeast end of the lake. Trees were cut, and pulled to the lake with horses whereupon they were floated down the lake, or pulled on sleds across the ice to the sawmill. This early logging activity around the lake may have contributed to the slight increase in sedimentation rate recorded between 1886 and 1900. The 1894 flood also may have contributed to this increase.

The sedimentation rate increased dramatically in the early 1900s, reaching a rate of 155 mg/cm<sup>2</sup>/yr, representing a 7-8 fold increase over background levels. This increased sedimentation rate coincides with increased human activities in the basin including construction of a railroad line for the Great Northern Railroad along the entire 7 mile southern shoreline of the lake. The terrain along the south lakeshore is steep in places, thus considerable earth moving, and road bed leveling occurred along the lakeshore. Rail preparations along the lake also included blasting through bedrock, excavation of a tunnel near the head of the lake, and construction of a trestle and filling of Beaver Bay on the lake's southwest shore. Most of the construction occurred over a several year period prior to the official opening of the railroad in 1904.

The following descriptions were made of the railroad work around Whitefish (taken from Trippett, 1956). "Land was surveyed (for the railroad) and hundreds of men worked clearing brush, clearing right of ways and building roads for freighting. Clouds of dust and debris filled the air as huge rocks and trees were blasted out. Inasmuch as there were no bulldozers in those days, horsedrawn slip scrapers were used to level the soil for the laying of track". The following was taken from Trippett (1956) who copied it from the local Whitefish paper, the *Pilot*, dated January 23, 1904. " In the vicinity of Whitefish, this (railroad) work has been particularly active. All along Whitefish Lake, the work is



progressing night and day....As much of the work is of a blasting nature, the heavy cannonading suggests active operations along the military lines."

There is little doubt that substantial amounts of sediment were dumped and/or washed into Whitefish Lake during construction of the rail line. This activity likely contributed to the sedimentation increase measured in the lake core during this period. In addition, early logging activity around the lake during this time period also may have contributed to increased sediment deposition in the lake. Unfortunately, I have found no comprehensive early logging records which allow estimation of land areas or timber volumes involved in the Whitefish Lake Basin.

The lake sedimentation rate declined following construction of the railroad. Nevertheless, the deposition rate from 1902 to 1908 was 62 mg/cm<sup>2</sup>/yr, which is 3 times higher than background levels estimated for the 1800s. Following completion of the railroad along the lakeshore, timber harvest was the primary human land disturbance activity in the Whitefish Lake catchment. Logging demand was fueled by the need for railroad ties as well as building materials for the new town of Whitefish (then called Stumptown), established in 1904. The Whitefish townsite, established in 1904, was located along the Whitefish River below the lake outlet. Thus clearance of land for the townsite did not likely contribute additional sediments to Whitefish Lake. A small sluice dam was operated at the outlet of Whitefish Lake for 10-15 years during this period, and lake level fluctuations associated with this dam may have increased shoreline erosion around the lake in the early 1900s.

During the early 1900s, logging activity in the catchment was limited to the immediately vicinity of Whitefish Lake and the adjacent railroad line. Little logging apparently occurred in upstream drainages since Swift Creek and other tributaries to Whitefish Lake were not suitable for carrying logs. Logging above Whitefish Lake in those days consisted of selective cutting of the larger trees in the immediate vicinity of Whitefish Lake, which were pulled to the lake using horses, and then floated (or skidded across the ice) to the sawmills (Schaffer and Engelter 1973). By 1904-1905, there were several sawmills in the area including the one on Whitefish Lake near the outlet, one downstream on the Whitefish River, and several others farther downstream on the Stillwater and Flathead Rivers. Logging camps sprung up around Whitefish Lake, and along the Whitefish River below the Lake.

The following two passages describe logging activities around Whitefish Lake around 1905. The first is from Schafer and Engelter (1973). "Lumber that choked the lake in spring was carried across the ice in winter. In the spring of each year, big log drives took the logs down the Whitefish River....". The second description was assembled by Dorothy Johnson, and printed as a footnote in Schafer and Engelter (1973). "Lumber companies were thick around Whitefish in those days and used to cut their logs along the lake then raft them down to the dam in great booms with steam and gasoline tug boats. Then when the logs reached the lower end of the lake they were held there till spring. When the ice went out in April or May and the water was running full, and the river was swift and unhindered, then they used to have log drives. They must have had them for at least ten years after we came to Whitefish before the timber was gradually thinned out and the mill at the dam took care of all that was left. "

The lake sedimentation rate increased to 88 mg/cm<sup>2</sup>/yr from 1908 and 1912. In addition to human land disturbance described above, the 1910 fires may have contributed to this increase.

The sedimentation rate declined to 29 mg/cm<sup>2</sup>/yr from 1912 to 1922. This decrease correlates with a decline in land disturbance activity in the catchment. Desirable timber around the lake apparently was depleted by earlier logging activities, and logging efforts shifted to other areas of the Flathead Basin.

1929-present. There was a large increase in sedimentation in Whitefish Lake for a short time period in the early 1930's (Figure 8). Sedimentation levels increased 10-fold over background, reaching levels up to 212 mg/cm<sup>2</sup>/yr. This large peak corresponds with extensive logging activities which commenced in 1929 in the Lazy Creek and Lower Swift Creek drainages above the head of Whitefish Lake. Although estimate of logging activity from the early 1900s are lacking, I was able to obtain estimates of acres harvested in the Whitefish Lake catchment from 1929 through the present time (Figure 9). Most of this acreage harvested in the 1930s was located on private lands owned by the Glacier Park Company (which was subsequently incorporated into the Burlington Northern Company and then split off into Plum Creek Timber Company).

A railroad spur was constructed from the head of Whitefish Lake up the Lazy Creek drainage during this time period. Trees were cut, pulled to the rail line using horses, and transported to the mills via railcar. The Lazy Creek

railspur was operated for three years, and then removed in 1932 (D. Klehm, pers. comm.). Thereafter, logs were hauled out of the Lazy and Swift Creek drainages by truck. Logging roads and skid trails were constructed throughout the areas being logged. During this period, there apparently was little concern about water quality impacts, and few, if any, regulations existed. Stream crossings were unrestricted, culverts were used infrequently, and "corduroy" roads were constructed across wet areas simply by clearing the trees and then placing timbers, side by side, across the wetlands, creating a road bed. These and other timber-related activities, including construction of the railspur, likely were major causes of enhanced erosion and sediment transport to surface waters.

The situation likely was compounded by large stream flows in the catchment during the spring of 1932 and 1933 (Schaffer and Engelter 1973). Comparatively low sedimentation rates following the large flood of 1894 suggest minimal increases in sediment deposition in the lake from an undisturbed catchment. However, high stream flows in the early 1930's likely accelerated the erosion and transport of sediment from areas disturbed by various logging-related activities in the catchment. There is distinct light grey, dense, band in the core at a depth corresponding to the early 1930s (Figure 5). This band probably resulted from enhanced erosion of inorganic sediments due to ground disturbance activities, without an accompanying increase in darker, less dense organic sediments from the soil or lake environment.

The correlation between logging activities and increased sedimentation in the early 1930's is striking and leaves little doubt concerning a cause and effect relationship between these two events. Thereafter, lake sedimentation rates declined in the mid to late 1930's in concert with declines in timber harvest activity (Figure 8).

During the mid-1930's the Civilian Conservation Corps (CCC) completed a road in the Whitefish Lake catchment which extended around the east side of the lake and up through the Swift Creek drainage. This road was used extensively for log hauling and appears to be the only other significant human-related land disturbance activity which may have affected sedimentation during the 1930's. However, the amount of land disturbance caused by the CCC road was small in comparison to area impacted by the network of roads, skid trails, and railspur used in the timber harvest efforts. The 1937 fire also may have contributed to sedimentation during this period. However the impact



of this fire is believed small, due to the limited aerial extent of the fire (750 acres), and the fact that it left no visible ash layer in the lake sediments (unlike the ash layer corresponding to the 1926 fire).

During the 1940's there was little timber harvest or road building activity in the catchment. Concurrent with the decline in timber harvest and associated activity, sedimentation rates in the lake declined to  $42.5 \text{ mg/cm}^2/\text{yr}$ . A road was built in the Whitefish Lake catchment up to the Big Mountain ski resort in 1947. Although there has been considerable development at the ski area, the vast majority of this activity is located in the Haskill Creek drainage, which is outside the Whitefish Lake Basin.

Logging and associated road building activity in the Whitefish Lake catchment commenced again in earnest in 1948, primarily on the Stillwater State Forest in the Swift Creek drainage. Harvest activities peaked around 1950, declined again, and then increased through the mid-1960s. This pattern of logging activity was correlated with similar changes in lake sedimentation. Lake sedimentation rates peaked at  $72 \text{ mg/cm}^2/\text{yr}$  around 1950, declined to  $52 \text{ mg/cm}^2/\text{yr}$  in the mid 1950s, and then increased over a ten year period, peaking at  $87.8 \text{ mg/cm}^2/\text{yr}$  in the mid-1960s.

During the two decade period from the late 1940's through the 1960's, timber harvest and accompanying road and skid trail construction occurred across large parts of the catchment on Stillwater State Forest Lands, and beginning in the early 1960's on Burlington Northern lands. During the first part of this time period, activities were concentrated on gently sloping valley bottoms. However, by the 1960's harvest and associated road building activities had moved up into steeper, more erosive areas. This twenty year period of timber harvest and associated activity appears correlated with sediment deposition in Whitefish Lake.

The 1964 flood occurred during the latter part of this trend. The sedimentation rate did not increase dramatically following this flood, the second largest on record. Rather, the sedimentation rate continued an increasing trend which was initiated in the 1950s. Although the 1964 flood likely contributed to increased erosion and sediment transport in the basin, the impact of this flood on lake sedimentation appears small in comparison to previous land disturbance activities.

From 1967-1971, the sedimentation rate declined to  $72.6 \text{ mg/cm}^2/\text{yr}$ , concurrent with a decline in logging activity in the late 1960s. From 1971 to

1983, the lake sedimentation rate was reduced to 54.7 mg/cm<sup>2</sup>/yr. Although timber harvest was elevated at the beginning of this period, harvest declined to low levels during the latter part of this period. The 1974 flood also occurred during this period. Foresters report that the 1964 and 1974 floods did not cause extensive erosion and gulying throughout the Whitefish Lake catchment. Rather, these floods resulted in considerable erosion and channel destabilization in the main stream courses and floodplains. Although the flood of 1894 suggests that flooding of undisturbed catchments may not result in greatly increased sedimentation rates compared to human disturbance activities, it is unclear whether the same may be said for floods occurring in catchments disturbed by timber harvest. For example, it is possible that the floods of 1964 and 1974 flushed out sediments from the larger streams which had accumulated there as a result of past activities.

Between 1983 and 1990, the mean sedimentation rate was 52.2 mg/cm<sup>2</sup>/yr. Timber harvest activities increased during this period; however, as in the 1970s, this increased harvest was not accompanied by comparable increases in sedimentation as in previous years. In addition to timber harvest activities, two other factors may have contributed to changes in lake sedimentation in recent years. First, the 1980 eruption of Mt. St. Helens produced a fallout of volcanic ash across western Montana. There is no visible ash layer in the study cores, and lake sedimentation rates did not appear to increase during this time period. Nevertheless, sediments were deposited in the basin as a result of this eruption. Second, recent increases in lakeshore housing and other developments along Whitefish Lake may have contributed sediments to the lake. Considerable areas of the shoreline still remain undeveloped. Although lake sedimentation rates did not increase during recent years, it is possible that observed sedimentation rates would have been lower in the absence of volcanic ash deposition and lakeshore development.

There are several factors which may explain the reduced sedimentation rate in Whitefish Lake during the 1970s and 1980s. First, this time period coincides with significant efforts on the part of government resource management agencies and the timber industry to attempt to reduce the impact of timber harvest activities on erosion and sediment transport to surface waters. A combination of mandatory and voluntary standards were adopted in an attempt to reduce the sedimentation risk. These efforts focused on minimizing erosion associated with road construction, stream crossings, and restricting



harvest activities on the most sensitive lands. The sedimentation data provide evidence that these more recent logging practices may have reduced the rate of sediment transport to Whitefish Lake, in comparison to previous timber harvest activities in the basin.

Although the recent reduction in lake sedimentation may support the effectiveness of newer logging practices in reducing sediment transport, this observation must be tempered by several important observations. First, the recent sedimentation rates are still well above background sedimentation rates estimated for the period prior to human settlement. Second, the 1980's have been characterized by a series of relatively mild run-off years (Figure 10). It is possible that subsequent flood events could dislodge sediments deposited in the flood plain and/or pools in the stream channel during the 1980's, and carry them into the lake. If this occurs, then lake sedimentation rates would increase, as these sediments, eroded during recent years, were finally transported into the lake.

Another factor may have contributed to the reduced lake sedimentation rate observed since the early 1970s. Recent timber harvest in the Whitefish Lake catchment has been concentrated on bottom lands where the erosion potential is reduced compared to the steeper, more erosive lands in the upper regions of the catchment which were logged during the 1960's. In fact, a significant portion of the land logged in the 1980's lies on Plum Creek Timber Co. lands in the Lazy Creek drainage, and represents harvest of timber regrown since the area was first logged in the 1930's. Reduced sedimentation also may be due to the fact that new road construction, a major source of sediments, was reduced somewhat in the 1980's due to availability of pre-existing roads in the drainage. Nevertheless, a portion of the recent logging activity lies on previously un-logged, steeper terrain (located on Stryker Ridge).

It is clear that recent logging efforts concentrated in the lower portion of the Basin have had less impact on sedimentation in Whitefish Lake, compared to the original roading, logging, and rail spur construction on many of the same areas in the early 1930's which produced a 10-fold increase in lake sedimentation. However, it is not clear from these data whether the recent logging practices including Best Management Practices (BMPs) have reduced sediment loadings in comparison to activities in the 1950s and 1960s. There is some evidence to suggest this; however before drawing definitive conclusions one must sort out the relative importance of improved practices together with

other potential causal factors such as use of pre-existing roads, a series of comparatively mild run-off years, and other factors which may affect sedimentation such as lakeshore housing development and the eruption of Mt. St. Helens.

A final observation on the sediment core from Whitefish Lake concerns the abrupt color change in the sediment core which occurred at a depth of 9cm which occurs around the year 1950 (Figure 5). The sediments above this area are light grey, while the sediments down to 15.5 cm ( ~1925) have a distinctly darker grey coloration. Closer examination of the darker band from 1920-1950 reveals a lighter grey matrix inter-mixed with fine black particles. This color change does not appear to be explained by any of the natural or human-related disturbances described previously. Insight into this color change was subsequently derived from reading in Schafer and Engelter (1973) a description of the old practice of cutting ice from area lakes for use as a refrigerant in ice-boxes. " During the late 40's, ice was usually cut at Lake Five (located 20 miles E of Whitefish) and then shipped by rail to Whitefish. Not only was Whitefish Lake ice was not thick enough in most winters, but it was topped with too many cinders. As the railroad switched (from coal burners) to diesels, this latter deterrent no longer posed a problem, and in 1950 and 1952 large-scale operations were carried on at Whitefish Lake".

### Swan Lake

The history of the Swan Lake Basin over the last 120 years includes a number of natural and human-related disturbance activities. There were large floods in 1894 and 1964. As in the other lakes, neither of these floods appeared to be accompanied by large changes in lake sedimentation. However, definitive conclusions about the 1894 flood are speculative for Swan Lake since this flood occurred within the oldest dated core section. There were no large fires in the Swan Basin during the period of record. Relatively small fires did occur in 1910, 1919, 1936 and 1963. The largest of these occurred in 1919 when several thousand acres burned, representing less than 1% of the Swan Lake drainage area. There were no visible ash layers in the sediment cores. Further discussion of natural disturbances is incorporated in the following chronological discussion of changes in the Swan Lake Basin.

The lowest sedimentation rate measured in Swan Lake over the 120 year period of record occurred from 1874 and 1899, prior to human disturbance activities in the basin (Figure 11). The mean sedimentation rate during this period was 16 mg/cm<sup>2</sup>/yr. During the first two decades of the 1900s, the sedimentation rate increased slightly to 19 mg/cm<sup>2</sup>/yr. There are a number of factors which may have contributed to this increase. First, the dating precision for these early dates is less certain than for more recent dates. Thus, this small increase in lake sedimentation may not be significant. Nevertheless, there were a number of land disturbance activities in the basin in the early 1900s which could have contributed to an increase in lake sedimentation.

A few small homesteads began to appear in the basin in the early 1900s. Cattle were brought into in the upper part of the basin near Condon around 1910; however, early cattle ranching efforts were abandoned in 1912 (Art Whitney personnel communication). Wildfires in 1910 fire burned a small portion of the basin above Condon. A road was built along the north shore of Swan Lake in 1916-1917. In addition, fires in 1919 burned several thousand acres near the head of Swan Lake. Finally, early logging activity commenced near the head of Swan Lake in 1914. During the late teens and early 20s logging activities intensified. A 3 mile-long railroad spur was built from the head of Swan Lake up to S. Lost Creek. Logs were cut and then pulled by horses down to South and North Lost Creeks. In addition, a sluice dam was built on South Lost Creek during this period (Art Whitney personnel communication). Water was released by blasting out the dam during spring run-off and large numbers of logs were swept downstream into the Swan River and subsequently into Swan Lake.

The mean lake sedimentation rate increased to 33.4 mg/cm<sup>2</sup>/yr for the period between 1920 and 1933. This increase represents a doubling over background levels during the late 1800s. There are a number of factors which may have contributed to this increase. Timber harvest activities including log drives and rail operation continued near the head of Swan Lake through the early 1920s. Log drives on S. Lost Creek and the Swan River likely caused considerable stream-bank erosion. The fires of 1919 and construction of a road along Swan Lake also likely increased sediment transport to the lake. Given the present information, it is not possible to estimate the relative importance of these various factors in contributing to increased lake sedimentation. The actual causes likely involve a combination of factors.



Some of the early land disturbance activities such as rail-line construction and early log drives appear to have preceded the lake sedimentation increase by several years or more. Delays in lake sedimentation could have been caused by the nature of the Swan River above Swan Lake. The Swan River passes through a broad meandering delta area which extends for several miles above the lake. This appears to be an area of sediment deposition. As such, this area could buffer, dampen, or delay transport of sediments from the river into the lake.

The increase in lake sedimentation in the early 1920s is consistent with early visual observations by Art Whitney (personnel communication). He noted that the water in the Swan River near Bigfork used to run "pretty clear" even during spring run-off. The first time he recalled the river being "murky" was during the spring run-off of 1921 and 1922.

The lake sedimentation rate declined to 27 mg/cm<sup>2</sup>/yr from the mid-1930s to the mid-1940s. This decline corresponds with a decline in land disturbance activity in the basin. From the mid-1920s to 1940, there was virtually no timber harvest or road construction in the Swan Lake basin. Fires burned a relatively small portion of the upper basin in 1936.

The mean sedimentation rate increased to 37 mg/cm<sup>2</sup>/yr for the time period between 1946-1957. This increase corresponds with construction of the Swan Highway as well as a resumption of timber harvest activities. Work on the new highway began in the late 1940s and included relocation of portions of the old road closer to Swan Lake. In particular, this work included bank excavation and filling along the lakeshore just north of the Swan Lake campground. By 1956, the road extended past the head of the lake, up to Goat Creek, some 15 miles above Swan Lake. The road reached the head of the drainage in the late 1950s.

In addition, substantial logging and associated road building activity commenced again in the Swan Lake drainage in the 1940s. Although I was unable to obtain accurate timber harvest estimates for the 1940s, the level of harvest was comparable to the 1950s (Art Whitney, personal communication). Logging roads and skid trails were built in the lower portion of the basin during this period.

Accurate timber harvest records begin in 1950 (Figure 12). Timber harvest and associated road building activities accelerated during the 1960s and lake sedimentation rates remained elevated during this period, reaching a

mean rate of 38 mg/cm<sup>2</sup>/yr from 1957 to 1972 (Figure 11). The 1964 flood also occurred during this time interval, and these flood waters may have accelerated sediment transport to the lake. However, as in the other two study lakes, this large flood did not appear to be correlated with a large increase in lake sedimentation. A small fire in 1963 burned less than 1000 acres in the upper portion of the Lost Creek basin and also may have contributed to lake sedimentation.

The lake sedimentation rate increased again to 49.5 mg/cm<sup>2</sup>/yr from 1972 to 1990. This sedimentation rate was the highest recorded over the 120 year period of record, some three-fold higher than background rates estimated for the late 1800s. This recent sedimentation increase is correlated with a large increase in logging activity and associated road building in the Swan Basin (Figure 12). During the 1980s, timber harvest activities doubled over the levels attained during the 1960s and 1970s. During this period, timber harvest and associated road building expanded on bottom lands as well as on the flanks of the Mission and Swan mountain ranges that enclose the Swan Valley. Much of this increased harvest occurred on private lands owned by Plum Creek Timber Company. Timber harvest on State and Federal lands declined slightly during this same time period (Figure 12).

Although timber harvest and related road building represent the largest human land disturbance activity in the basin in recent years, there has been an increase in construction of lakeshore cabins and homes around Swan Lake. This activity also may have contributed to increased lake sedimentation. Nevertheless, large areas of lake shoreline remain undeveloped.

Comparisons between Swan Lake and Whitefish Lake yield additional insight into the impact of lakeshore development on lake sedimentation rates. The lakeshore area around Whitefish Lake also has experienced home and recreational development. Recent development around Whitefish Lake appears comparable, or may even exceed that around Swan Lake. However, in contrast to Swan Lake, recent sedimentation rates in Whitefish Lake do not appear to have increased. Thus it is unlikely that lakeshore development is responsible for the recent large increase in sedimentation in Swan Lake. Rather, the contrasting lake sedimentation responses appear more closely related to differences in recent timber harvest and road building activities in the two basins. As described earlier, recent timber harvest activities in the Swan Basin far exceed past acreages subject to harvest in the Basin. By contrast, recent



timber harvest acreages in the Whitefish Basin fall within the level of activity reached several times over the last 60 years.

As in Whitefish Lake, the lack of large flushing flows in recent years may have resulted in substantial accumulation of sediments in the river system. This could be more of a factor in Swan Lake than Whitefish Lake, given the low gradient, depositional area in the river, immediately above Swan Lake. If so, then subsequent flushing flows could carry large quantities of previously eroded material into the lake.

### Lake McDonald

As in the other study lakes, the lowest sedimentation rate in Lake McDonald was recorded at the beginning of the period of record. Between 1880 and 1910, the sedimentation rate was  $7 \text{ mg/cm}^2/\text{yr}$  (Figure 13). The sedimentation rate increased to  $10 \text{ mg/cm}^2/\text{yr}$  between 1910 and 1935, and then increased substantially to  $29 \text{ mg/cm}^2/\text{yr}$  over the period between 1935 and 1945. These increases appear to coincide with construction of a two lane highway, called the Going to the Sun Road, which passes through a large part of the Lake McDonald catchment. This major road runs along the south shoreline of Lake McDonald for much of its 9 mile length, and continues up the drainage along McDonald Creek for 11 miles, closely bordering the creek in numerous locations. The road then switches back up the along steep exposed terrain within the Lake McDonald catchment leading up to Logan Pass on the Continental Divide. Roadbed preparation included construction of numerous embankments along steep areas, blasting tunnels through bedrock, and considerable earth moving activities, all of which undoubtedly contributed sediments to surface waters.

Although the initial road was completed in the early 1930's, the sedimentation rate in Lake McDonald did not peak until the late 1930's, reaching a level of  $29 \text{ mg/cm}^2/\text{yr}$ . This apparent lag in lake sedimentation may have resulted from a delay in transport of sediments from the upper portion of the catchment down into the lake. Such delays could be due to the long distance between road building activities on the erosive slopes near the continental divide and Lake McDonald. In addition, the heavily forested streams in the McDonald Creek Basin, may have higher sediment retention rates compared to logged catchments. Natural downfall in the stream bed serve

as stream sediment traps. Furthermore, unlogged catchments may have smaller maximum stream flows compared to logged catchments, which could result in reduced sediment flushing capacity in undeveloped catchments (see Hauer, Module A). Thus there are a number of factors which may have contributed to the apparent delay in sediment deposition in Lake McDonald.

The sedimentation rate declined rapidly in the 1960s. Revegetation and stabilization of the original road cuts likely reduced sediment delivery to surface waters along the road. This reduction also may have been partially due to stabilization of the road surface by paving in the 1950s. It is possible that periodic regrading of the road together with road dust stirred up by cars along this heavily travelled road may have contributed to elevated sedimentation levels in Lake McDonald. After the road was paved, the potential contribution of road dust to lake sedimentation would have been greatly reduced.

The mean sedimentation rate for the 29 year period from 1961 to the present declined to  $14 \text{ mg/cm}^2/\text{yr}$ . This rate is roughly twice the rate estimated for the late 1800s. Reasons for the continued existence of sedimentation levels above background are speculative. The 1980 eruption of Mt. St. Helens left no visible band of sediments in the core. However, it is possible that this eruption resulted in increased sediment deposition in Lake McDonald. Thus, it is possible that in absence of this eruption, the most recent sedimentation rate may have been closer to levels measured in the late 1800s. In addition, there have been limited human activities in the basin which could have contributed to recent sedimentation rates. These include ongoing maintenance on the road, as well as limited construction projects around the lake. However, future plans call for significant "improvement" along much of the Going to the Sun Road.

Although the Going to the Sun Road represents the largest human land disturbance activity in the Basin, there has been some other limited development around the lake. This includes construction of several lodges along the lakeshore as well as small lakeshore cabins limited to the extreme east and west ends of the lake. Much of this activity occurred in the early part of this century, and does not appear to have noticeably influenced mean lake sedimentation rates shown in Figure 13.

Natural disturbance events did not appear to be closely correlated with major changes in sedimentation rate in Lake McDonald. As in the other study lakes, there were no large fires in the basin during the period of record. One of the larger fires in the catchment occurred in 1967, when approximately 5% of

the catchment burned. In addition, the 1964 flood occurred during this interval. Sedimentation rates during the time interval following the flood and fire remained well below those achieved during the 1940s and 1950s. Sedimentation rates may have increased for a short time after these events, however any such increases were dampened out by subsequent sedimentation rates. Smaller fires in 1926, 1937 may have contributed to increased sedimentation in Lake McDonald; however, the impact of these natural disturbances are likely masked by the road building activities.

None of the McDonald Basin fires or floods left visible bands in the sediment core during the 110 year period of this study. However, a thick black band is visible in the Lake McDonald core at a depth of 18-19 cm, which is below the oldest strata dated in this study (Figure 6). This band may correspond to extensive fires which burned during the year 1735. Several large fires burned portions of the Lake McDonald Basin that year, including much of the steep landscape leading down to the shoreline of Lake McDonald (Barrett 1988). Sedimentation rates must have increased dramatically in Lake McDonald following this large fire, given the appearance of this thick (1 cm) ash layer in the lake sediments. Unfortunately, I was unable to estimate the actual sedimentation rate during this period since current sediment dating techniques are not available for close estimation of dates over 150 years old.

## MANAGEMENT IMPLICATIONS

This study indicates that past land disturbance activities are correlated with increased sediment deposition rates in all three study lakes. Sedimentation rates increased 3 to 10 fold over background levels, corresponding with logging, road building, and/or railline construction in the catchments. Results of the BMP audits revealed that the greatest number of BMP deviations were related to road drainage and road maintenance (Potts, Module F). Lake sediment analyses suggest that over time, the sediment contribution from roads (such as the Going to the Sun Highway) are greatly reduced. Recent sedimentation rates in Whitefish Lake provide equivocal evidence for reduced sedimentation rates using newer forest practices. However, sedimentation rates in Swan Lake reached their highest estimated level within the last 15 years concurrent with a doubling of timber harvest activities in the basin in the last 10 years. Results from Potts (Module H) indicate that a few areas in the Swan



Drainage had an unusually high concentration of harvest activities. Water quality violations resulting from recent timber harvest activities also have occurred in the Swan Basin. Therefore, if recent forest practices employed in the 1970s and 1980s do indeed reduce sediment delivery compared to older practices, then any such improvement appears to have been offset by the recent large expansion of harvest activities at least in the Swan Lake Basin. Furthermore, additional evidence from the study lakes suggests that sediments resulting from past disturbance activities may still be in transit in the river system above Swan and Whitefish Lakes. Thus, sediment loadings associated with past activities may increase in the future.

Since increased sedimentation may have negative impacts on both stream and lake environments the large increases in sediment loadings documented in the present study represent an important environmental concern regarding both past and projected activities. Hauer and Blum (Co-op Module C) reported increased that timber harvest activities were correlated with increased suspended sediments, nutrients and algal growth in streams. These results are consistent with studies of timber harvest in other areas (Likens et al. 1970, Lowe et al. 1986). Weaver and Fraley (Co-op Module D) showed that increased levels of fine sediments in fish spawning areas in streams may substantially reduce the spawning success and viability of bull trout and Westslope cutthroat trout. These species are native to the Flathead Basin and have been designated sensitive species by the U.S. Fish and Wildlife Service and species of special concern by the state of Montana.

Unfortunately there are no comparable "paleo" techniques available for quantifying historical changes in the sediment composition in important salmonid spawning and rearing areas of streams. However, since the majority of lake sediments transported to lakes, enter via streams, past large increases in erosion, transport, and subsequent deposition of fine sediments in the lake environment would likely have been accompanied by increased deposition of sediments in portions of the stream channels upstream from the lake environment. Thus I expect that past increases in lake sedimentation documented in this study have had negative impacts on stream ecosystems in these catchments. The fact that estimated sedimentation rates in Swan Lake reached their highest levels within the last 15-20 years raises concerns about the potential negative impact of these sediments on important bull trout and



Westslope cutthroat trout streams above Swan Lake, and the effect of future land disturbance activities on these streams.

Another concern regarding increased sediment loadings to surface waters is undesirable stimulation of algal productivity and lake eutrophication. Sediments represent a major source of nutrients to surface waters (Mortimer 1941; Perry and Stanford 1982). Data from the Flathead Basin show a close correlation between suspended sediment concentrations in streams and stream nutrient (phosphorus and nitrogen) concentrations (Spencer and Hauer 1991, Ellis and Stanford 1988, Stanford and Ellis 1988, Stuart 1983, Golnar 1985). Detailed nutrient budget analyses from Whitefish and Flathead Lakes indicate that 60-70% of the annual phosphorus and nitrogen loadings come from stream inputs, with the bulk of this input associated with turbid spring run-off and un-related to point source inputs (Stanford and Ellis 1988, Stuart 1983, Golnar 1985).

Lakes serve not only as sediment traps, but also nutrient traps. Golnar (1985) estimated that 74% of the phosphorus entering Whitefish Lake was retained in the lake. While some nutrients may become permanently buried in the lake sediments, a portion of the nitrogen and phosphorus pool entering the lake environment remains in the water column. In studies on Flathead Lake, Dodds, Priscu, and Ellis (1991) showed that phosphorus and nitrogen could be recycled in the water column in a matter of hours or less. Thus, past increases in nutrient loadings are still likely affecting the lake ecosystems.

Phosphorus and nitrogen availability have been shown to be the primary factors limiting algal production in lakes in the Flathead Basin (Dodds et al 1989, Spencer and Ellis 1990). Stanford and Potter (1976) and Perry and Stanford (1982) hypothesized that stream sediments in the Flathead Basin, upon entering the lake environment, may settle out and strip phosphorus and algae from the lake water column. However Stuart (1983) disproved this hypothesis and concluded that algal production in Flathead Lake appeared to be stimulated by sediment additions. Furthermore, controlled bioassay experiments demonstrate that addition of sediments from a variety of locations in the Flathead Basin stimulate algal growth (Perry and Stanford 1982, Ellis and Stanford 1986, 1988). Although the bioavailability of phosphorus contained in turbid spring run-off in the basin may be only 6% (Ellis and Stanford 1988), this still represents the largest single nutrient source to Flathead Lake (Stanford and Ellis 1988). Thus, enhanced erosion and sediment transport, as documented in this study, have undoubtedly contributed to nutrient enrichment of the study lakes. Nutrient enrichment is the primary cause of lake eutrophication, an

undesirable process that may lead to stimulation of algal growth, reduced water clarity, oxygen depletion and other related problems (Wetzel 1988).

At present, Whitefish Lake is in a transitional state between oligotrophy and mesotrophy (Golnar 1985). Late-summer hypolimnetic oxygen depletion already is occurring in the lake. Golnar (1985) concluded that Whitefish Lake lies near a critical threshold of "excessive" phosphorus loading, as determined from the nutrient loading model of Vollenweider and Kerekes (1980). Other lakes in the Flathead Basin also are threatened by increased nutrient loadings. Flathead Lake also is undergoing eutrophication as evidenced by increased algal production (Stanford and Ellis 1988). As with Whitefish Lake, scientists have described Flathead Lake as being on a threshold, such that increased nutrient loadings seriously threaten water quality in the lake (Bahls 1986, Stanford and Ellis 1988). Other lakes in the Flathead Basin including Swan Lake, Ashley Lake and Lake Mary Ronan develop summer hypolimnetic oxygen depletion and also are at risk from increased nutrient loadings.

During 1990, dissolved oxygen (DO) measurements in Swan Lake showed development of severe hypolimnetic oxygen depletion in the south basin of the lake (Figure 14). Slight oxygen depletion, noted in June, expanded through the summer and fall. By mid-October, the bottom 7-10 m of the water column showed a pronounced oxygen deficit, with concentrations near the bottom declining to 0.5 mg/L. This appears to be the lowest dissolved oxygen measurement recorded in any of the large lakes in the Flathead Basin which are noted for their water quality. There are smaller seepage-type lakes in the basin (e.g. Echo, Loon, and Foy's Lake) which have more severe dissolved oxygen depletion, together with algal blooms and reduced water quality which characterize these more productive lakes.

Two limnological studies of Swan Lake conducted in the mid-1970s also reported dissolved oxygen depletion in Swan Lake. Sonstelie (1974) reported a minimum DO concentration of 7.6 mg/L in 1973 while a USEPA (1976) study reported a minimum concentration of 5.4 mg/L in 1975. Unfortunately, these measurements were made at depths of only 15 and 17m respectively; no measurements were made in the two deep basins of the lake where depths reach 35-40 meters and where more extensive oxygen depletion could have occurred. Although the DO concentration of 0.5 mg/L reported in 1990 is significantly lower than any previously reported level in Swan Lake, there is insufficient historical data to say with any certainty that DO concentrations have declined significantly since the mid-1970s. Nevertheless, reduction of hypolimnetic oxygen levels to near anaerobic conditions in Swan Lake

(regardless of past history) is surprising and alarming, especially given the short water residence time in the lake.

The existing data documenting substantial oxygen depletion in Swan Lake, have led to the lake being described as an impaired lake (Loren Bahls, Montana Water Quality Bureau, personnel communication). The reduced oxygen concentrations in the South Basin undoubtedly exclude trout and salmon from portions of the water column in late summer and fall. Other aquatic organisms such as *Mysis relicta* (opossum shrimp) appear to avoid the South Basin in late summer (Rumsey personal communication). Evidence from numerous scientific studies indicate that if oxygen concentrations decline just a little bit more in Swan Lake, then one can expect a rapid increase in available phosphorus in Swan Lake (Mortimer 1941, Wetzel 1988). This would be caused by the release of sediment-bound phosphorus into the lake water when oxygen concentrations decline to 0 mg/L at the sediment-water interface. If this happens, the eutrophication process would accelerate rapidly, leading to a deleterious cycle of further oxygen depletion, which in turn would stimulate more widespread release of sediment-bound phosphorus into the lake water. Such changes would likely lead to serious declines in water quality including nuisance algal blooms, poor water clarity and degradation of fisheries habitat. This negative scenario of events has been documented in numerous lakes in other parts of the country, frequently fueled by increased human activities and development in the lake basin.

The USEPA (1976) estimated that 99.7% of the total phosphorus load to Swan Lake was from non-point sources. Unfortunately, there are insufficient data available at present to allow compilation of a comprehensive nutrient budget for Swan Lake in 1990, or to fully explain the cause of the dissolved oxygen depletion in the lake. There may be other important sources of nutrients and/or organic loadings to the lake that also have contributed to current water quality conditions, e.g. shoreline homes, upstream development, and natural sources. However, regardless of the actual cause, the reduced oxygen levels in Swan Lake raises serious concerns about any future increases in nutrient loadings to the lake.

Available data provide evidence that increased sediment loadings have negatively impacted stream and lake resources in the Flathead Basin. Symptoms of aquatic resource degradation include elevated fine sediment levels in key bull trout and cutthroat spawning streams (Weaver and Fraley, Module D), and increased sediment loadings to lakes. The cause and effect relationship between increased fine sediment loading (from whatever source) and spawning habitat degradation is well understood. However given the limited data available on nutrient budgets for the study



lakes, it is more difficult to assign a direct causal relationship between increased sediment loadings and lake water quality. Nevertheless, there is no question that sediments represent a significant source of nutrients to lakes in the Flathead Basin. Increased nutrient loadings to lakes typically lead to increased productivity, and given sufficient productivity, periodic oxygen depletion and algal blooms.

The present study provides evidence for a link between past human land disturbance activities (primarily related to timber harvest and road building) and increased fine sediment (and nutrient) loadings to lakes. These data provide evidence from the Flathead Basin that human disturbance activities appear to increase fine sediment deposition in lakes to a greater extent than natural disturbance events. Similar conclusions have been drawn from studies in other regions (Hutchinson et al. 1970, Davis 1975, Batterbee et al. 1985, see reviews in Berglund, 1986).

Considerable efforts are presently being made to reduce the input of nutrients to lakes in the Flathead Basin, in an attempt to maintain the high water quality which characterizes many of its lakes. Examples of nutrient control measures being employed include a ban on the sale of phosphate detergents in 1985 and nearly \$20 million dollars invested in construction and/or expansion of wastewater treatments plants and collection facilities for phosphorus removal. New, or upgraded treatment plants, are either in place or under construction for all major communities upstream from Flathead Lake. Similar efforts should be directed at other controllable nutrient sources in the basin such as timber harvest and related road building and road maintenance.

## CONCLUSIONS

1. Lake coring analyses indicated that past human land disturbance activities were correlated with increased fine sediment deposition up to 10-fold in Whitefish Lake, 4 to 5-fold in Lake McDonald, and 3-fold in Swan Lake.
2. Lake McDonald
  - a. Initial road construction and upgrading of the Going to the Sun Road from Lake McDonald to the continental divide at Logan Pass during the 1930's and 1940's were followed by substantial increases in sediment deposition in Lake McDonald.



- b. After the road was paved in the early 1950's the sediment deposition rate in Lake McDonald declined substantially; however, sedimentation rates still remain above background levels.

### 3. Whitefish Lake

- a. Large increases in sediment deposition occurred during the early part of this century (1900-1910) and were attributed to railroad construction along the lakeshore, logging activity around the lake, and the 1910 fires.
- b. The largest sedimentation increases occurred in the early 1930's when substantial logging and associated road and railline construction were concentrated in the Lazy Creek drainage and Lower Swift Creek, near the head of Whitefish Lake.
- c. Sedimentation rates also were elevated near 1950 and again in the 1960s. These increases were largely attributed to substantial logging and associated road building activity, which extended to upper portions of the Whitefish Lake drainage.
- d. Recent logging activities in the Whitefish catchment appears to have had less impact on lake sedimentation than past activities. Possible explanations for reduced sediment impacts include use of pre-existing roads, logging on less-erodible lands, improved logging and road building practices, and a series of comparatively mild run-off years.

### 4. Swan Lake

- a. Sedimentation rates increased during the 1920's following a number of land disturbance activities including road construction, fires, and timber harvest activities that included sluice dams, log drives, and rail line construction.
- b. Sedimentation rates increased again in the 1950s in concert a resumption of timber harvest and road building activities.
- c. From the early 1970s up to the present, the lake sedimentation rate reached its highest level. This increase occurred as timber harvest intensified, more than doubling the previous maximum harvest level in the Basin.

- 5. Results from the three study lakes suggest that roads represent the greatest disturbance activity resulting in increased fine sediment transport and deposition in the downstream lakes. Once constructed, the sediment contribution appears to decline.

6. Changes in deposition of fine sediments directly attributed to natural stream banks, floods, fires, and other natural erosion processes during the past 150 years were much smaller than changes attributed to human disturbance activities in these two catchments. Previous speculation that erosion of naturally unstable stream banks and other natural sources may mask sediment inputs attributed to human activities appear unfounded with respect to fine sediment deposition in Whitefish Lake, Swan Lake, and Lake McDonald.

## RECOMMENDATIONS FOR FUTURE STUDIES

I recommend that lake basins supporting future, long-term timber harvest and road building activities have a monitoring program designed to document the impact of these activities on lake water quality. Current water quality monitoring efforts in the Flathead Basin are focused primarily on Flathead Lake and tributary streams. However, there are a number of smaller lake basins in the area which support significant logging activities but have little water quality monitoring information. Lakes in this category which are valued for their water quality and/or fisheries resources include Swan, Whitefish, Ashley, Lake Mary Ronan, and others. We urge immediate emphasis on Swan Lake given the recent evidence of oxygen depletion in the lake together with extensive land use activities in the basin. Monitoring efforts should include a combination of in-lake monitoring for documentation of lake conditions as well as upstream monitoring to document various source areas including site specific inputs from new activities in the basin.

Monitoring activities should include establishment of sediment and nutrient budgets for the basin (for non-point sources as well as point sources such as septic systems and wastewater effluent), Secchi depth transparency, phytoplankton abundance (chlorophyll *a* in the lake), as well as dissolved oxygen and temperature profiles. We recommend that serious consideration be given to analysis of additional sediment cores from Swan Lake as well as a sediment core from Bowman Lake which has had no human land disturbance activity. In addition, we recommend development of some simple sediment accumulation monitors (traps) that could be placed at key locations Swan Lake and other lakes of interest. These collection devices would serve as continuous monitors of sediment delivery into the lake environment. Annual monitoring of sediment accumulation in these traps over a period of years would yield extremely valuable information concerning changes in sediment and nutrient loadings. These data should be integrated with continuous monitoring of sediment in the streams.

## REFERENCES

- Appleby, P.G., and F. Oldfield. 1978. The assessment of lead-210 data from sites with varying sedimentation rates. *Hydrobiologia* 103: 29-35.
- Bahls, L. L. 1985. Flathead Lake's midlife crisis. *Montana Outdoors*. 17: 18-22.
- Barrett, S.W. 1988. Fire History of Glacier National Park: McDonald Creek Basin. Final Report to Glacier National Park, West Glacier, Montana. 32p.
- Battarbee, R.W. et al. 1983.  $^{210}\text{Pb}$  dating of Scottish lake sediments, afforestation and accelerated soil erosion. *Earth Surface Processes and Landforms*. 10: 137-142.
- Berglund, B.E. 1986. Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons, New York. 869p.
- Davis, M.B. 1975. Erosion rates and land use history in Southern Michigan. *Envir. Cons.* 3: 139-148.
- Dodds, W.K, K.R. Johnson, and J.C. Priscu. 1989. Simultaneous nitrogen and phosphorus deficiency in natural phytoplankton assemblages: theory, empirical evidence, and implications for lake management. *Lake and Reservoir Man.* 5: 21-26.
- Dodds, W., J. Priscu, and B. K. Ellis. 1991. Seasonal uptake and regeneration of inorganic nitrogen and phosphorus in a large oligotrophic lake: size fractionation and antibiotic treatments. *J. Plank. Res.* (in press).
- Ellis, B.K. and J.A. Stanford. 1986. Bioavailability of phosphorus fractions in Flathead Lake and its tributaries. Report to the U.S.E.P.A. Duluth, MN.
- Ellis, B.K. and J.A. Stanford. 1988. Phosphorus bioavailability of fluvial sediments determined by algal assays. *Hydrobiologia* 160: 9-18.
- Ellis, B.K. and J.A. Stanford. 1988. Nutrient subsidy in montane lakes: fluvial sediments versus volcanic ash. *Verh. Internat. Verein. Limnol.* 23: 327-340.
- Golnar, T. F. 1985. Limnology of Whitefish Lake, northwest Montana. M.S. thesis. University of Montana, Missoula. 91p.
- Hutchinson, G.E., et al. 1970. *Ianula*: An account of the history and development of the Lago di Monterosi, Latium, Italy. *Trans. Amer. Phil. Soc., N.S.*, 60:(4), 178pp.
- Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher, and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook Catchment ecosystem. *Ecol. Monogr.* 40:23-47.



- Lowe, R.L., S.W. Golladay and J.R. Webster. 1986. Periphyton response to nutrient manipulation in streams draining clearcut and forested catchments. *J. N. Am. Benthol. Soc.* 5:221-229.
- Moore, J.N., J.S. Jiwan, and C.J. Murray. Sediment geochemistry of Flathead lake, Montana. Report to the U.S. E.P.A. Univ. of Montana, Missoula. 203 p.
- Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. *J. Ecol.* 29: 280-329.
- Pennington, W. R.S. Cambray, and E. M. Fisher. 1973. Observations on lake sediments using fallout  $^{137}\text{Cs}$  as a tracer. *Nature* 242:324-326.
- Robbins, J.A. and D.N. Edgington. 1975. Determination of recent sedimentation rates in Lake Michigan using  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$ . *Geochim. Cosmochim. Acta.* 39. 285-304.
- Perry, W.B. and J.A. Stanford. Algal growth stimulus by phosphorus in Flathead Lake, Montana, sediments. *Northwest Science.* 56: 48-52.
- Robbins, J.A. J.R. Krezoski, and S.C. Mozley. 1977. Radioactivity in sediments of the Great Lakes: post-depositional redistribution by deposit-feeding organisms. *Earth and Planetary Science Letters.* 36, 325-333.
- Schaffer, B. and M. Engelter. 1973. Stump Town to Ski Town. Whitefish Library Asso. Inc., Caxton Printers, Ltd. Caldwell, Idaho. 286 p.
- Shapiro, J. The core-freezer-a new sampler for lake sediments. *Ecology* 39: 758.
- Sonstelie, L.C. 1974. A study of the water quality of twelve lakes in the Flathead Drainage Basin. Flathead Valley Community College.
- Spencer, C.N. and B.K. Ellis. 1990. Co-limitation by phosphorus and nitrogen, and effects of zooplankton mortality, on phytoplankton in Flathead Lake, Montana, U.S.A. *Verh. Internat. Verein. Limnol.* 24: 206-209.
- Spencer, C.N. and F.R. Hauer. 1991. Phosphorus and nitrogen dynamics in streams during a wildfire. *J. N. Am. Benthol. Soc.* 10: 24-30.
- Trippett, F. 1956. Historical Highlights. Trippet Publishers, Kalispell, Montana. 80 p.
- Stanford, J.A. and D.S. Potter. 1976. The Flathead Lake River ecosystem: a perspective, pp. 241-250 IN Andrews, R.D. III, et al. (eds) *Terrestrial and Aquatic Ecological Studies at the Northwest Symposium Proceedings*, March 26-27, 1976. Eastern Washington State College Press, Cheney.

- Stanford, J.A. and B.K. Ellis. 1988. Water quality: status and trends, pp. 11-32. IN: Our clean water - Flathead's resource of the future. Proceedings of a conference held April 25-26, 1988, Kalispell, Montana. Flathead Basin Commission, Governor's Office, Helena, Montana.
- Stuart, T.J. 1983. The effects of freshet turbidity on selected aspects of the biogeochemistry and the trophic status of Flathead Lake, Montana, U.S.A. Ph.D. dissertation. University of Montana, Missoula, Montana. 229p.
- U.S.E.P.A. 1976. Preliminary report on Swan Lake, Flathead County Montana, EPA Region VIII. National Eutrophication Survey.
- Vollenweider, R.A. and J. Kerekes. 1980. The loading concept as a basis for controlling eutrophication philosophy and preliminary results of the OECD Programme on Eutrophication. Prog. Wat. Tech. Vol. 12, Norway, pp. 5-18. IAWPR/Pergamon Press Ltd.
- Wetzel, R.G. 1988. Limnology. 2nd ed. W.B. Saunders, Philadelphia. 357 p.

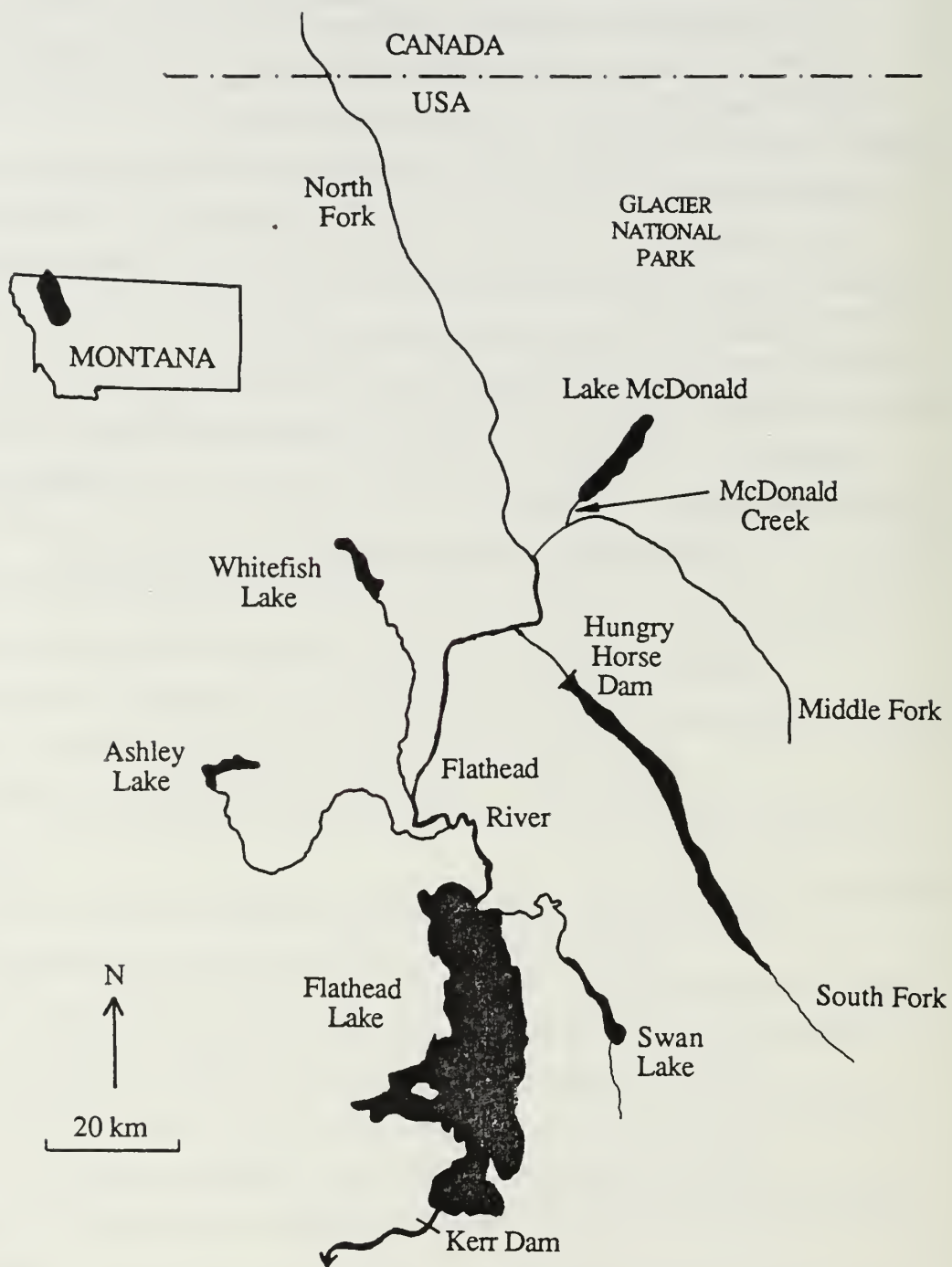


Figure 1. Map of the Flathead Basin showing the location of the three lakes from which sediment cores were collected (Whitefish, Swan, and McDonald).



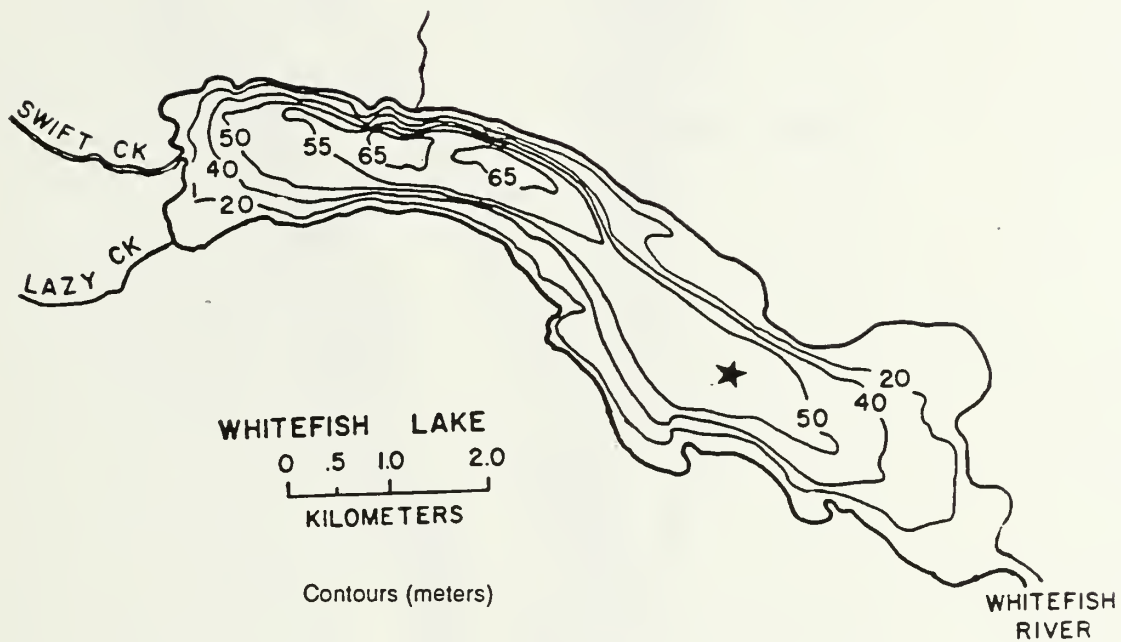


Figure 2. Bathymetric map of Whitefish Lake. Collection site for the core chosen for detailed analysis is indicated (★).

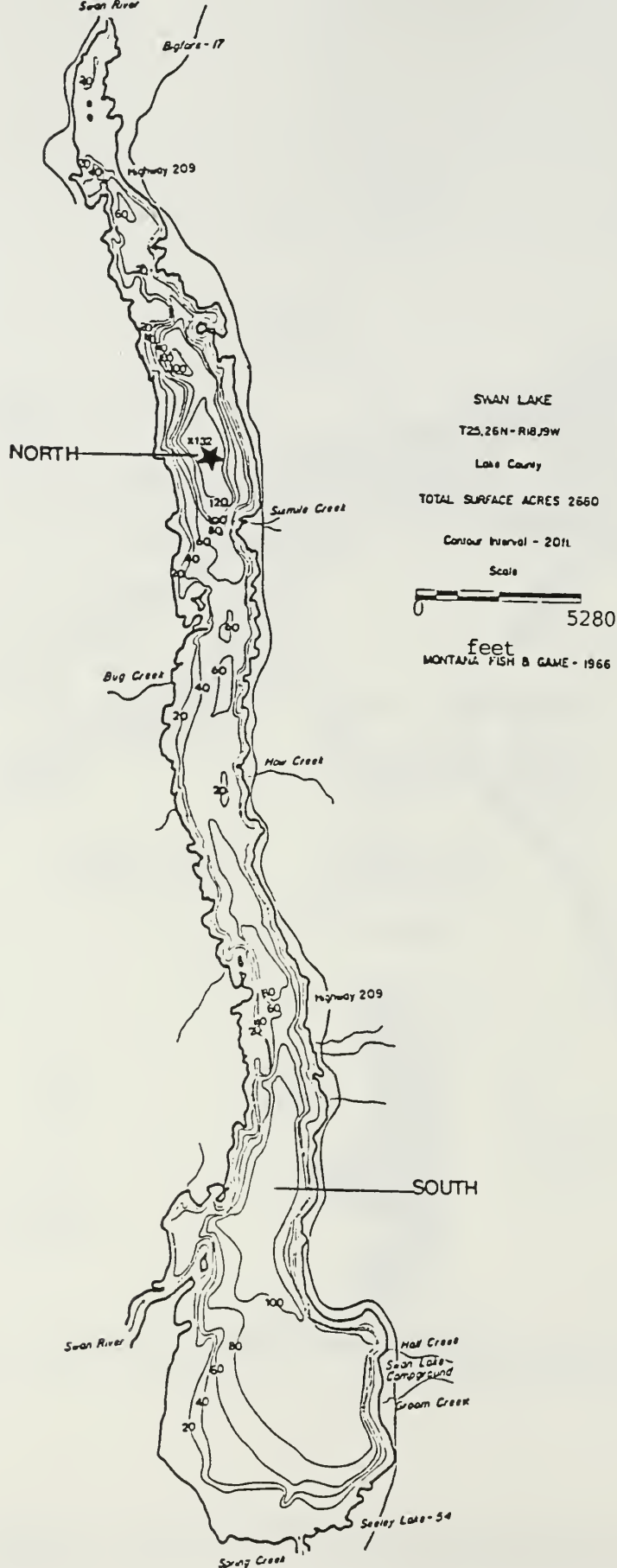


Figure 3. Bathymetric map of Swan Lake. Collection site for the core chosen for detailed analysis is indicated (\*).

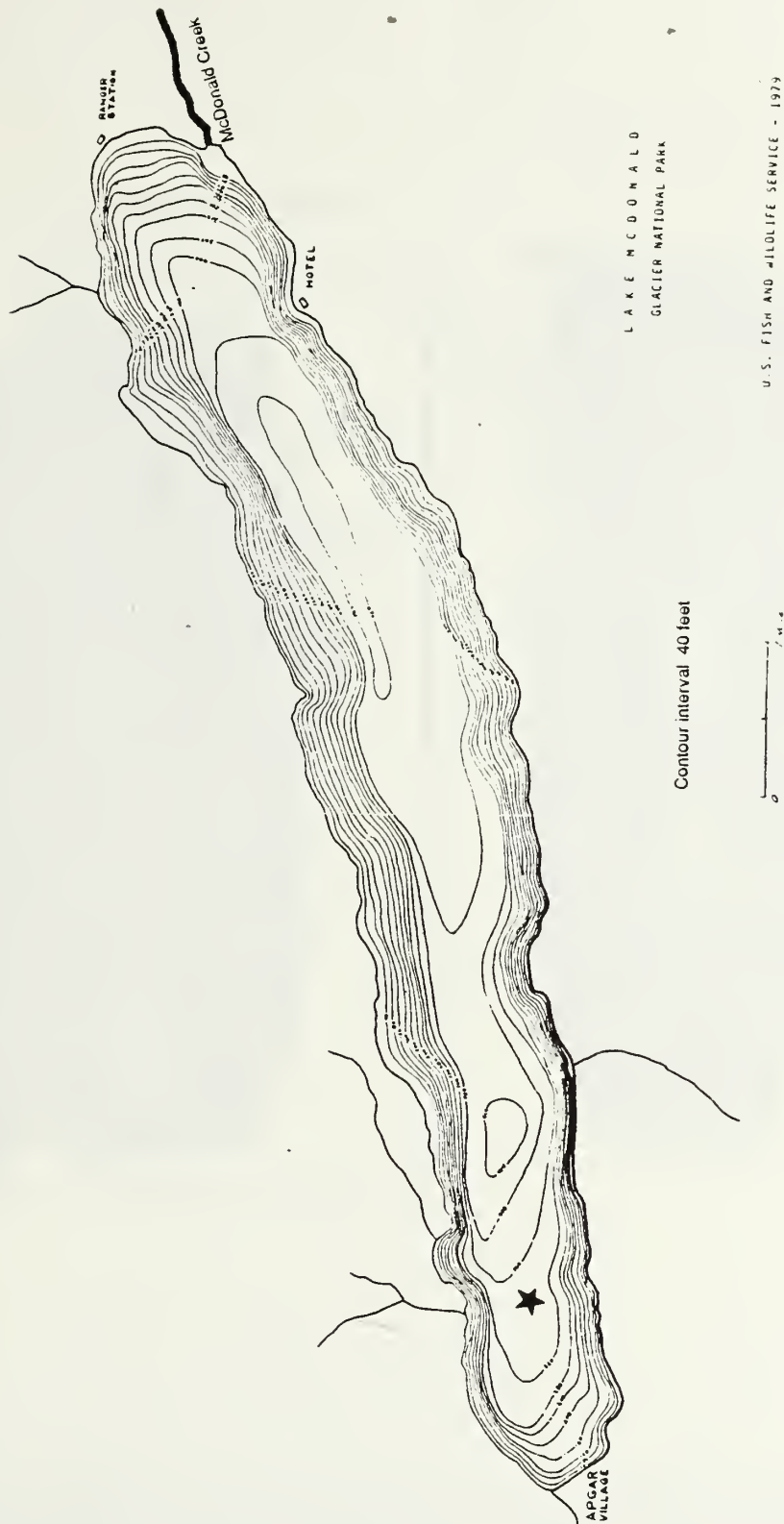


Figure 4. Bathymetric map of Lake McDonald. Collection site for the core chosen for detailed analysis is indicated (\*).



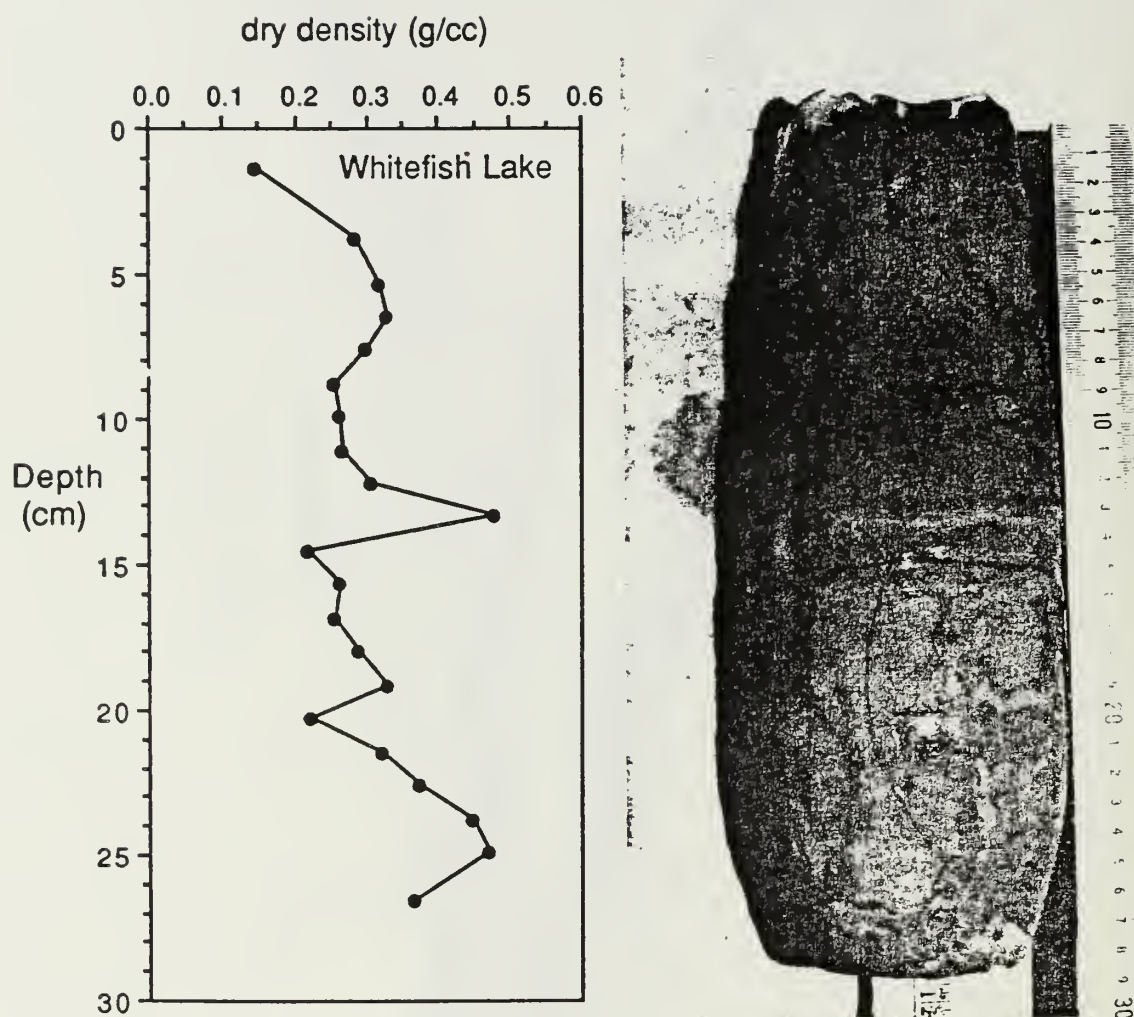


Figure 5. Photograph of the Whitefish Lake core and a plot sediment density (dry wt./cc) versus sediment depth. The two graphics are aligned so that the vertical scales are identical.

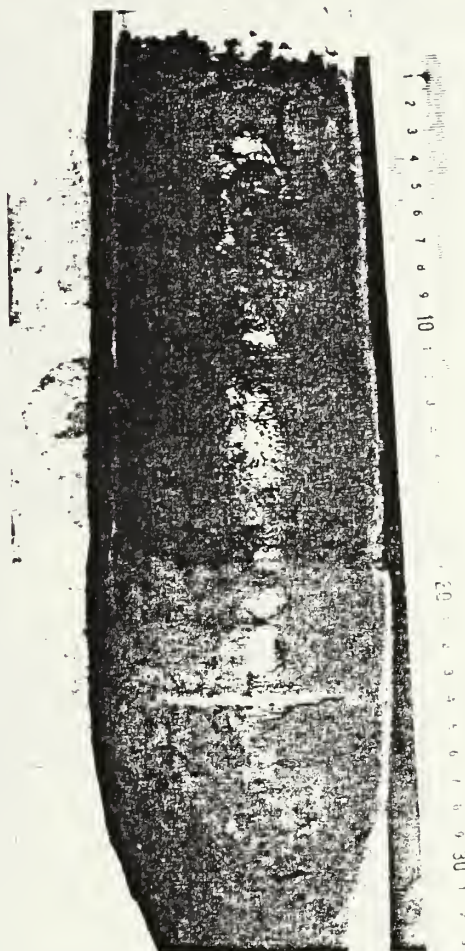
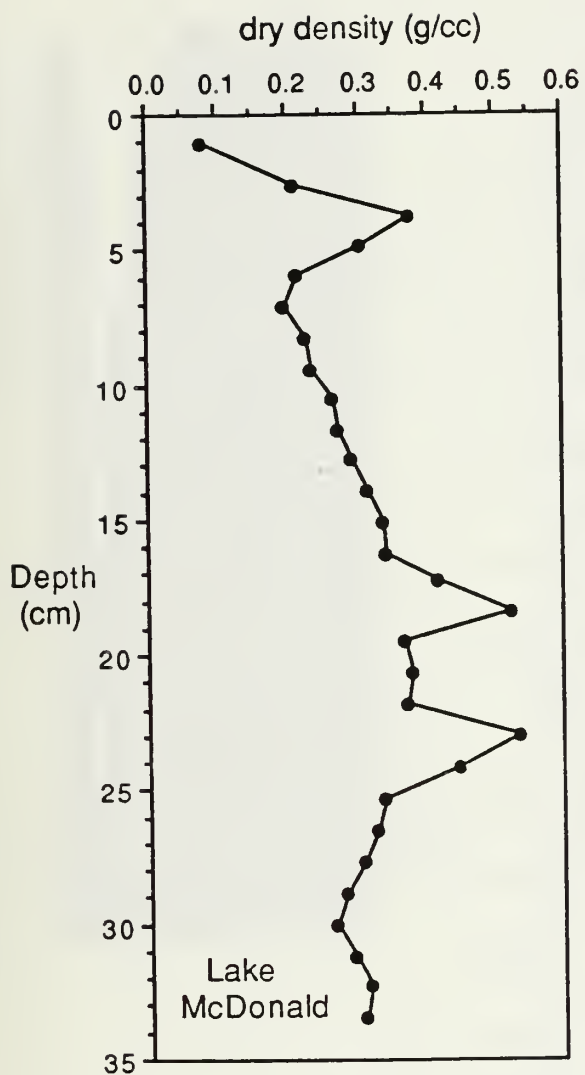


Figure 6. Photograph of the Lake McDonald core and a plot sediment density (dry wt./cc) versus sediment depth. The two graphics are aligned so that the vertical scales are identical.

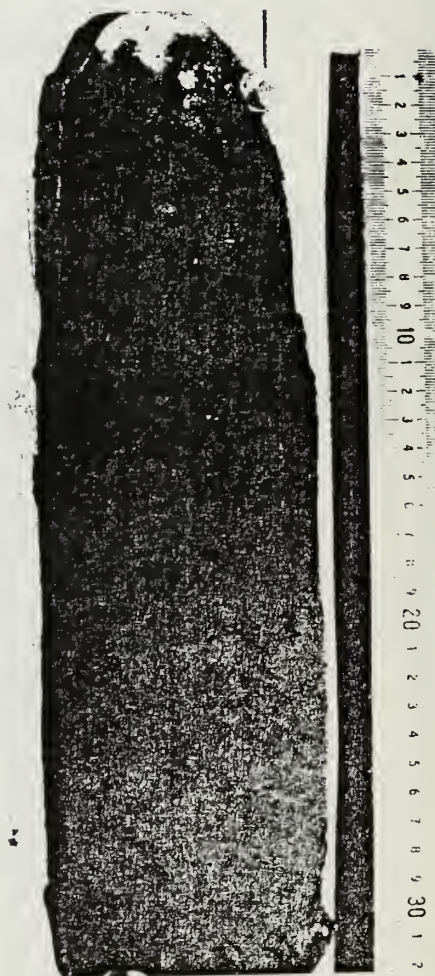
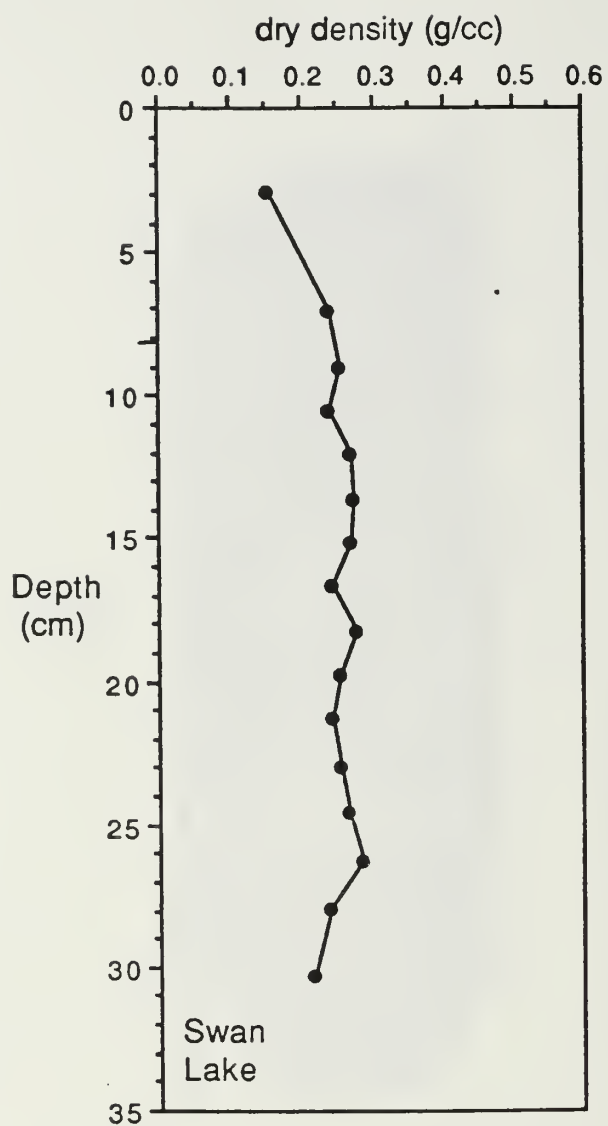


Figure 7. Photograph of the Swan Lake core and a plot sediment density (dry wt./cc) versus sediment depth. The two graphics are aligned so that the vertical scales are identical.



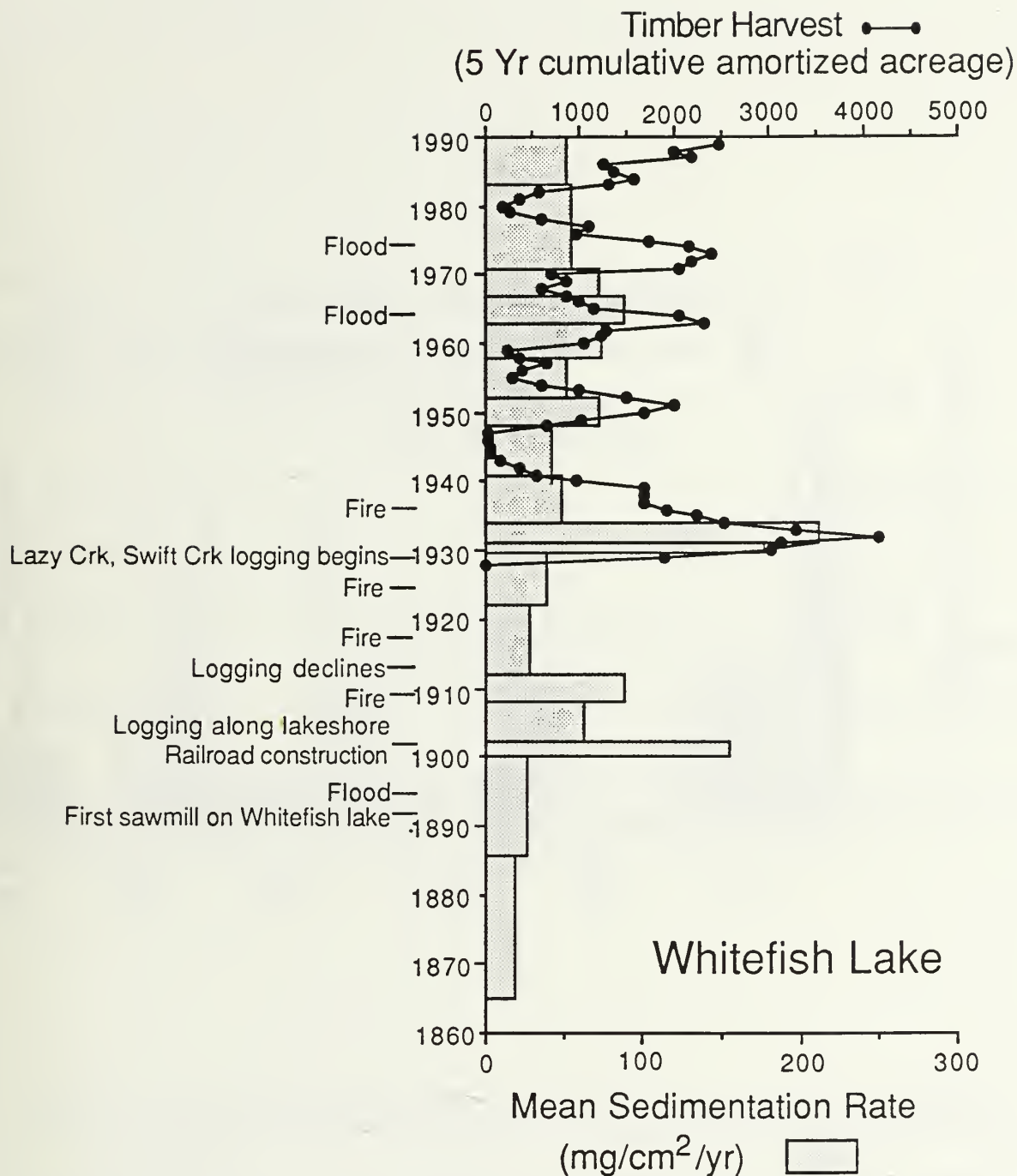


Figure 8. Mean sediment accumulation rates in Whitefish Lake over the last 125 years, and timber harvest activity over the time period (since 1929) when harvest records could be assembled. This latter activity is expressed as a 5 year cumulative acreage, with previous 4 years acreages amortized using the Flathead National Forest new road sediment delivery amortization coefficients.

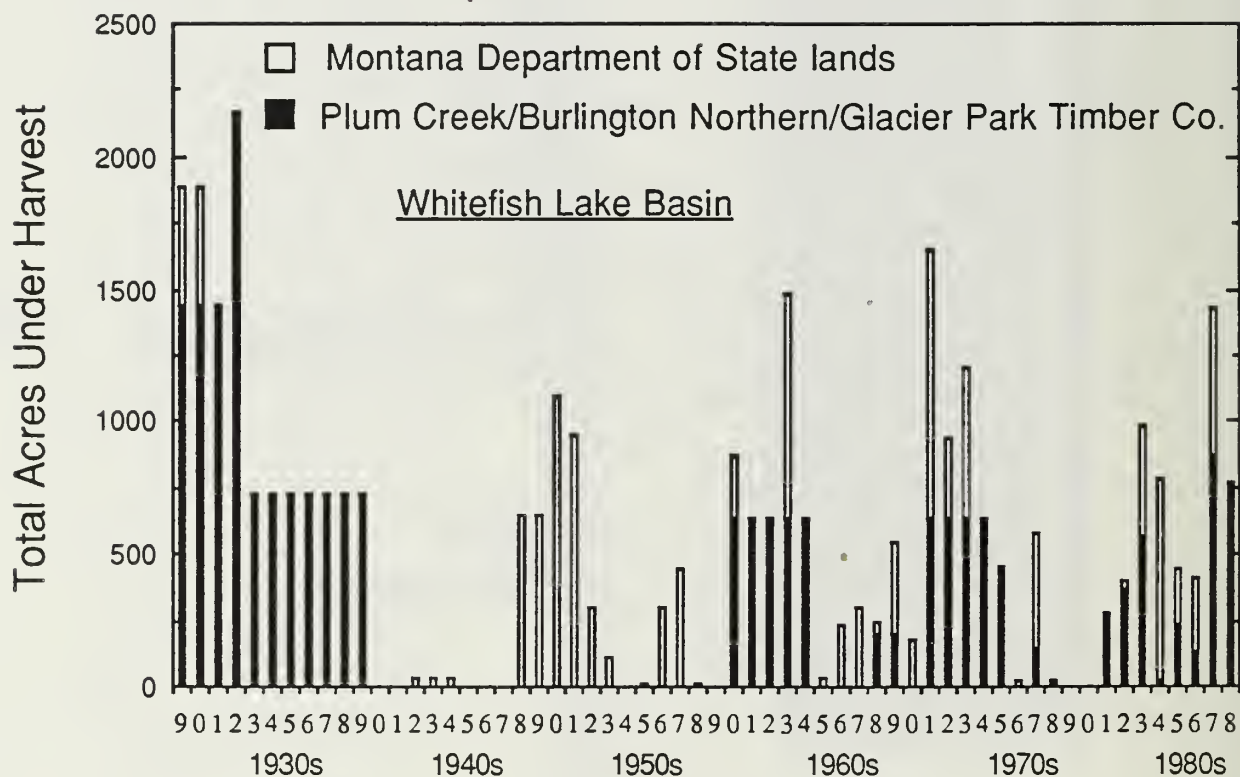


Figure 9. Timber harvest activity in the Whitefish Lake Basin during the period when records were available (since 1929).

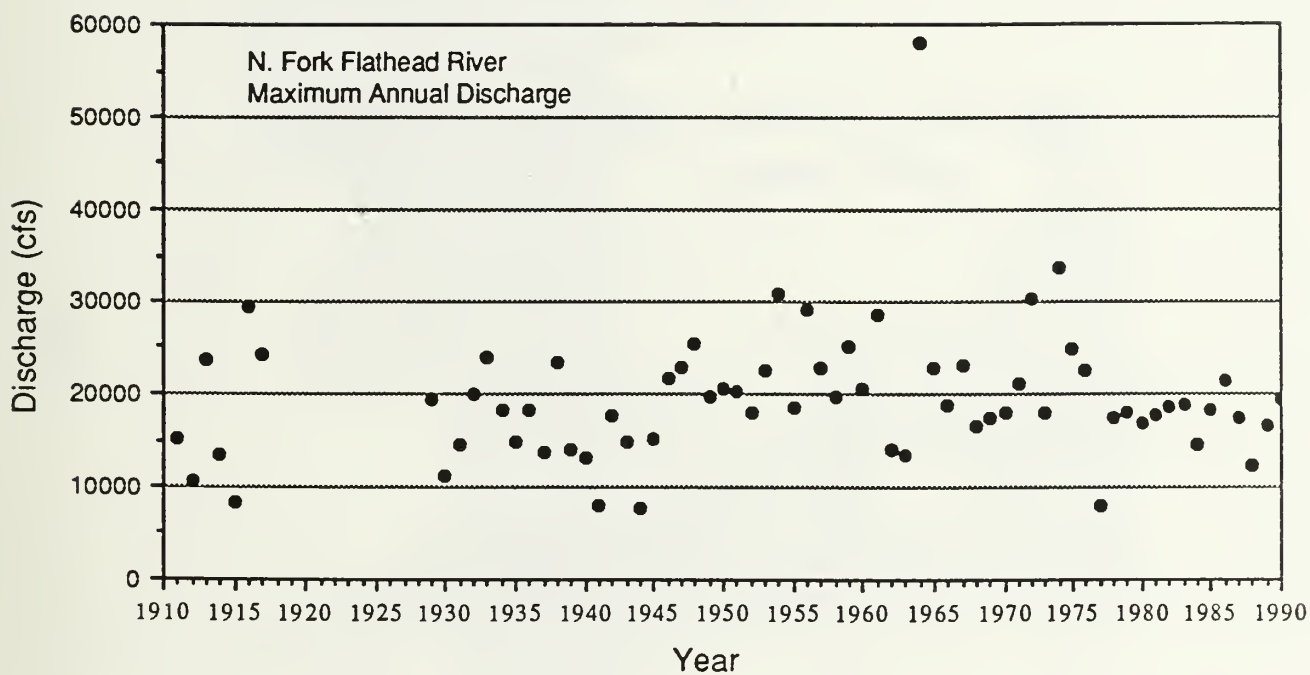


Figure 10. Maximum annual discharge in the North Fork of the Flathead River at Columbia Falls from 1910 to 1990. The gaging station did not operate from 1918-1928.



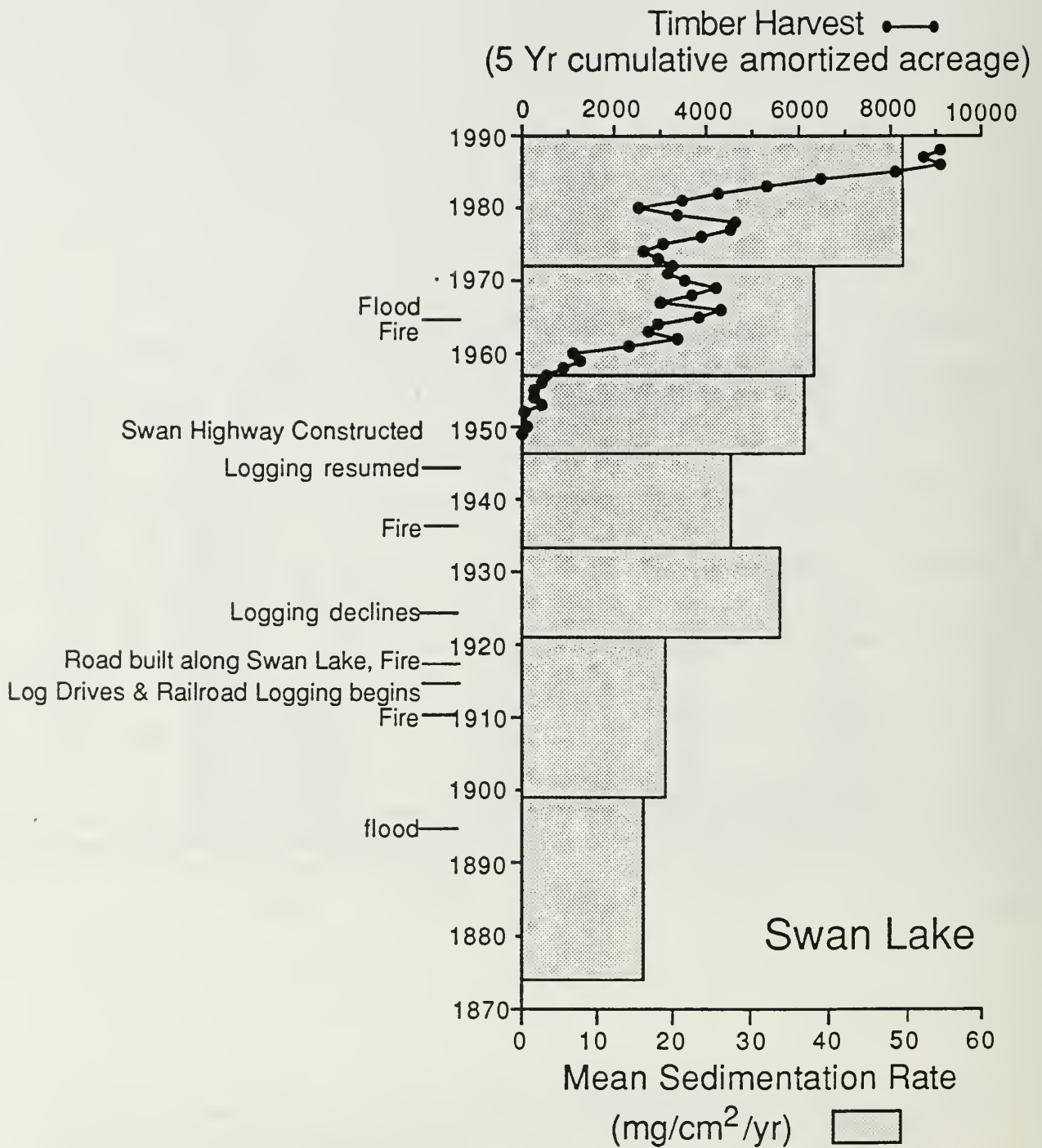


Figure 11. Mean sediment accumulation rates in Swan Lake over the last 125 years, and timber harvest activity over the time period (since 1929) when harvest records could be assembled. This latter activity is expressed as a 5 year cumulative acreage, with previous 4 years acreages amortized using the Flathead National Forest new road sediment delivery amortization coefficients.

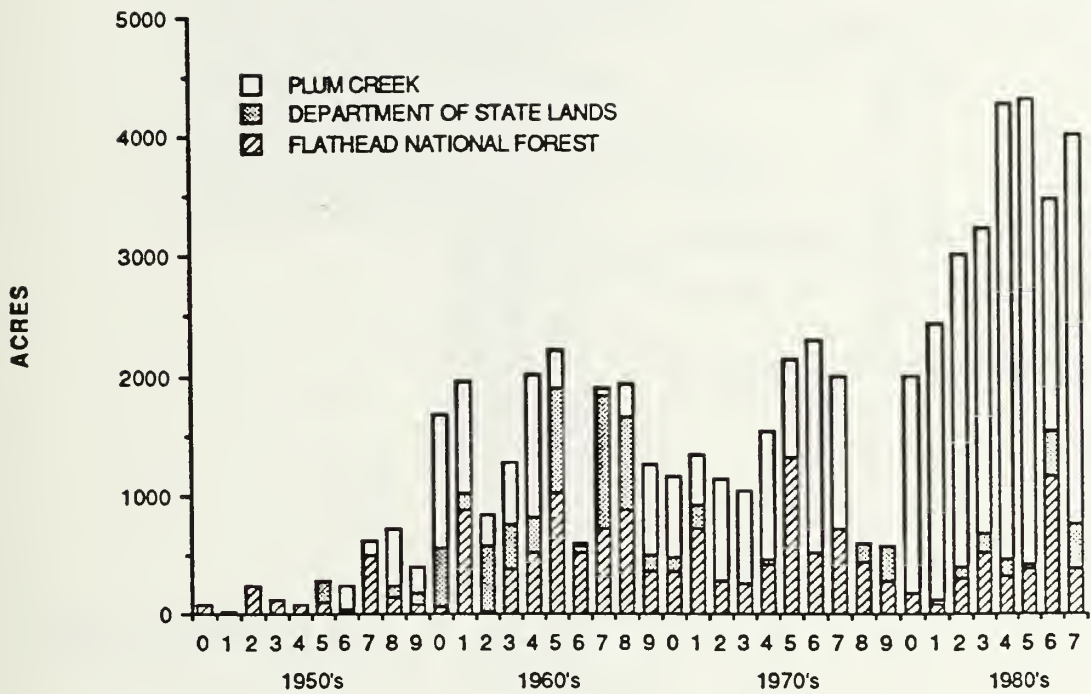


Figure 12. Timber harvest activity (equivalent clearcut acres) in the Swan Lake Basin during the period when records were available (since 1950).

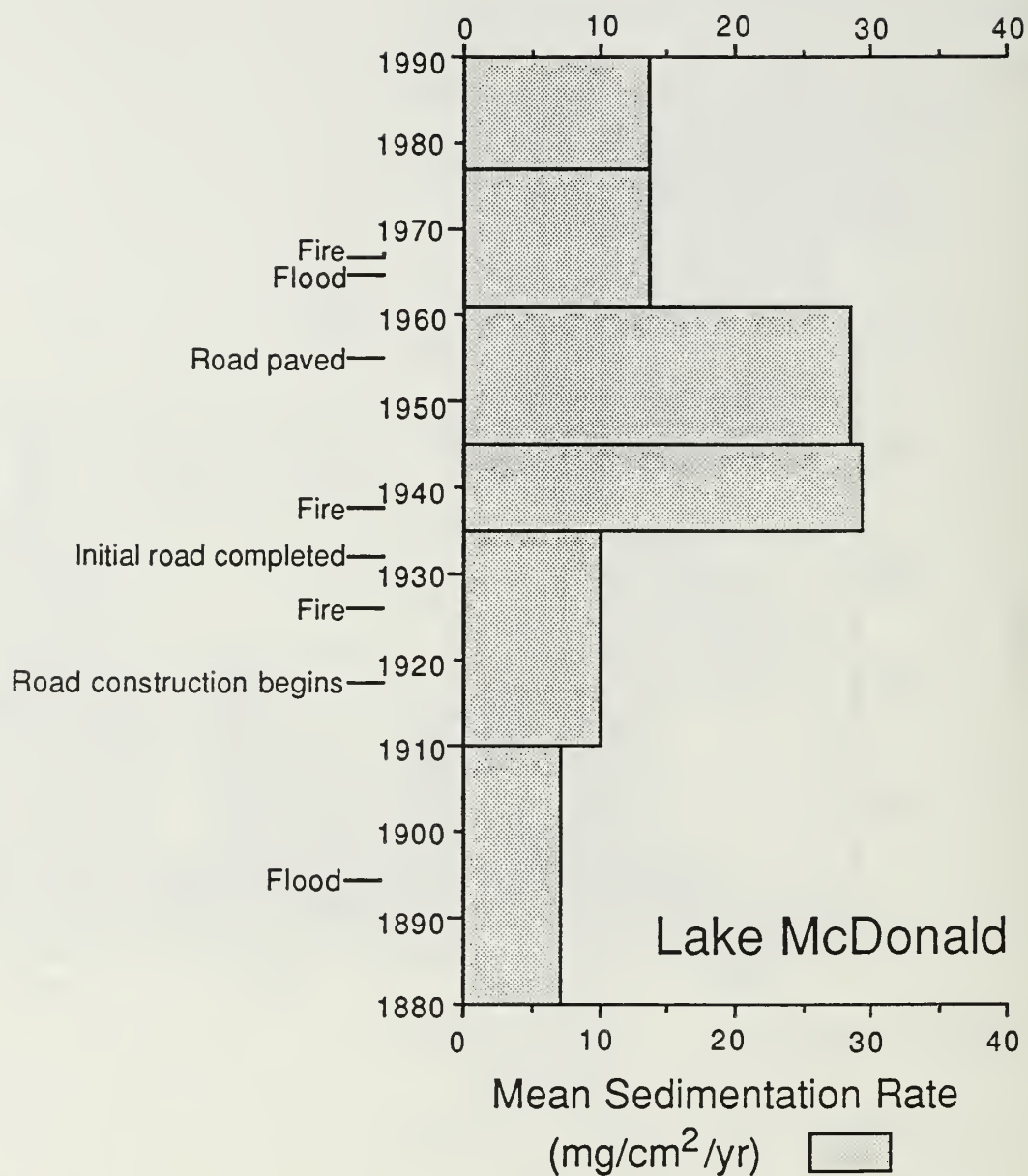


Figure 13. Mean sediment accumulation rates in Lake McDonald over the last 135 years.



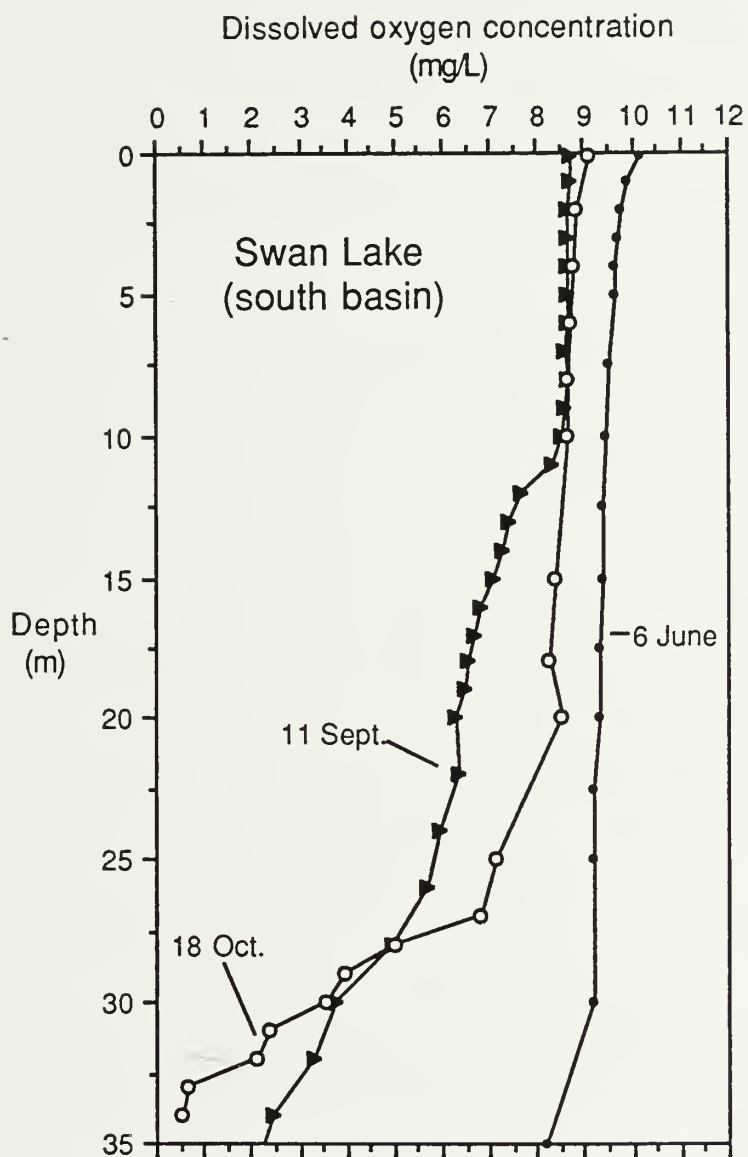


Figure 14. Dissolved oxygen profiles in Swan Lake (south basin) on three dates during 1990. These data were collected in a separate project in cooperation with the Montana Department of Fish, Wildlife, and Parks.





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